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CRITICAL REVIEW OF METHODS TO PREDICT THE BUFFET CAPABILITY OF AIRCRAFT

Helmut John

Advisory Group for Aerospace Research and Development

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on

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by

H.John

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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AGARD Report No.623

CRITICAL REVIEW OF METHODS TO PREDICT THE BUFFET CAPABILITY OF AIRCRAFT

by

Dr Helmut John

Messerschmitt-Bölkow-Blohm GmbH
Munich, Germany.

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PREFACE

Studies on the buffet characteristics of aircraft in the transonic speed range raise considerable analytical difficulties, which have been of great concern to designers. Due to the complexity of the flow field beyond the buffet boundary, theoretical solutions to the buffet problem are impossible at the present time. Therefore researchers are attempting to develop new wind-tunnel test techniques and establish correlation factors to flight test results.

The following paper presented by Dr John gives a state-of-the-art of methods used in Europe to predict buffet boundaries and response. A comprehensive survey of practical techniques and analyses is made and a critical review of their respective capabilities and limits of validity is presented.

This pilot paper is extremely useful and should help designers to solve their practical problems and, at the same time, highlight deficiencies and identify gaps that call for future work.

B.LASCHKA
Chairman, Airframe Response to
Transonic Separated Flow Working Group

CONTENTS

CRITICAL REVIEW OF METHODS TO PREDICT THE BUFFET PENETRATION CAPABILITY OF AIRCRAFT

by

Dr. Helmut John

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SUMMARY

According to the nature of buffeting as the wing-flexible response to the fluid motion, including exciting forces of separated flow, the most favourable test technique implies the use of dynamically scaled flexible models. Nevertheless, a number of techniques are based on the use of semi-rigid models and yield good results in comparison with flight tests. Methods covered in this critical review are: the possible relation - ship between buffeting intensity and mean loads; the dynamic analysis of unsteady wing root bending moments, and the use of fluctuating pressure measurements to predict the buffet penetration capability of aircraft.

This report contains a survey of methods which are in use in European countries.

NOTATION

c	chord
$\bar{c}$	mean aerodynamic chord
d_n	total damping
f	frequency
g	gravitational constant
k_n	reduced frequency
p	pressure
q	dynamic pressure
s	semispan
x,y,z	coordinates
c_L	lift coefficient
c_M	pitching moment coefficient
c_D	drag coefficient
c_B	Buffeting coefficient
c_p	pressure coefficient
A	aspect ratio
C	stiffness
D	damping
K	transfer function or constant of proportionality
M	mass
M_o	Mach number
P	force
S	wing area
α	incidence

η	fraction of semispan
ϱ	density
ϵ	strain
ω	circular frequency
Λ	sweep angle

Indices

n	number of mode
r	ratio
TE	trailing edge

Abbreviations

PSD	Power Spectral Density
RMS	Root Mean Square Value
SEP	Specific Excess Power

1 INTRODUCTION

1.1 General

The object of this paper is to present a general survey of methods for predicting the buffet penetration capability of aircraft which are used at present in the various European countries with aeronautical interests. In the past ten years, novel practical techniques have been developed and employed, and it has become necessary to make a critical review of their respective capabilities and of the specific conditions of their use.

The increased attention that is being given to studies of buffet characteristics by aerodynamicists is resulting from the present trend in combat aircraft development. This trend is currently demanding greater manoeuverability in the transonic flight regime. The performance of a transport aircraft and the manoeuvre capability of a combat aircraft can be severely limited by flow seperations on the wing, which causes buffeting and which can be accompanied by a variety of adverse effects, such as, for example, increase in drag, losses in lift and stability, pilot impairment, reduced tracking ability and fatigue problems.

Figure 1 illustrates the influence that these limiting factors can have on the performance of a fighter. This figure also shows the sensitivity of turn rates to typical boundaries at subsonic, transonic and supersonic speeds. The shaded area represents the region where the manoeuvre performance is reduced as a result of buffeting. Figure 1 also includes an agility plot which shows specific excess power (SEP) versus turn rate.

Not only the aerodynamic performance in terms of turn rates or g-levels is affected by buffeting, but also structural aspects need to be considered. In view of the fatigue life of the structure for the pilot in his cockpit environment, for weapons aiming and for systems like gyros etc., knowledge of amplitude ratios, vibration levels and predominant frequencies is of vital necessity for designers, and should be the objective of a project orientated evaluation with high priority.

1.2 Definition of Buffeting and Related Phenomena.

As a consequence of the occurrence of regions of separated flow on the wing at a certain incidence, the performance of an aircraft might be limited either by vibration or by degradation in handling characteristics. To this latter category belong phenomena like "pitch up", "wing dropping", "nose-slice" and "wing rocking". In Figure 2 a comparison of the predicted wing-drop boundary with the moderate buffet boundary is shown for a swing-wing fighter at 25° and 45° degrees of sweep. The estimation is done on the basis of coefficients $c_{n\beta}$ and c_{np}, taking the point where in the incidence range at small side slip angles, these coefficients change sign. As can be expected for $\Lambda = 25°$, the three boundaries compare very well, due to the 2-dimensional character of the flow. At $\Lambda = 45°$ where a "mixed type of flow" is encountered, a more gradual development of separation is to be expected, and the difference between the quoted criteria is obvious, leaving room for speculations up to which boundary the aircraft can be handled.

The highly undesirable rigid body motions of aircraft at incidences above separation onset are referred to in the longitudinal motion as "bouncing", "pitch-up" and "porpoising", while for the lateral motion "wing rocking", "wing dropping" and "nose-slicing" phenomena are known. The phenomena of "pitch-up", "wing-dropping" and "nose-slicing" are relatively well understood, resulting in a deficiency in longitudinal, lateral or directional stability, possibly leading to loss of an aircraft in extreme situations. The phenomena of "bouncing", porpoising" and "wing rocking" are a degradation in handling but not necessarily a limitation to sustained manoeuvres. While "wing bouncing" is typically associated with a rigid body heaving mode of the aircraft for "porpoising" and "wing rocking", an appropiate model is not yet established. It may either be an autonomous oscillation, better known as "limit cycle", in which nonlinear mean aerodynamic forces become significant, or an aerodynamically forced response to fluctuating pressures. There also exists the possibility of a limit cycle oscillation in which the periodic fluctuations in the flow field are coupled deterministically to the motion of the wing. Typically, the motion referred to as "wing rocking" is, as shown in Figure 3, primarily occurring in the roll-rate trace at frequencies lower than those associated with airframe flexible response in a fluctuating rigid body motion.Therefore, those phenomena of the second category belong to the flight mechanical problem area, and do have a direct effect on controllability and the ability to hold an accurate flight path. Phenomena of the first category, mentioned above, and which are associated with flexible modes of the aircraft structure can be said to influence "ride quality", and are referred to as "flight in turbulence" and "buffeting". The difference between turbulence and buffet is given by the basic difference of the driving force, while the structural behaviour of the elastic system is the same. The driving force of turbulence is embedded in the on-coming free airstream and can be defined by a finite wave length and spectrum. Turbulence, therefore, can be encountered at any incidence and flight condition.

Any elastic system fed with energy is subject to instabilities, and for an aircraft in flight, the energy is provided by the propulsion system which maintains the relative airflow around the exposed components of the aircraft. The instability

phenomenon of the structure is known as "flutter". The instability phenomenon of the relative airflow is associated with separation and produces the driving forces known as buffet, while buffeting is the flexible response to the fluid motion. The vibration level or buffeting intensity, defined by local accelerations or displacements at either natural or forced frequencies, is the result of the perturbation of the system and the energy loss of the oscillating component due to damping. If the energy gain is larger than the damping forces, a rapid failure of the structure will occur, and the integrity of the structure will be lost.

An excellent survey of the phenomena discussed above, is given by Jones (1), wherein theoretical models and differential equations in use are also discussed.

This present report concentrates on wing buffeting at transonic speeds only.

1.3 Theoretical Aspects

Of major importance in buffeting investigations are aerodynamic disturbances that produce driving forces for the airframe structural response, called buffeting, which finally establishes the attained vibration level. Theoretical structural models defining the dynamic properties of the structure have been used for years to provide informations on flutter speeds and gust analysis. Starting from stiffness and mass distributions, the so-called modal analysis allows the calculation of natural frequencies, mode shapes and generalized masses. Those results can be compared and corrected using ground vibration tests.

With regard to buffet forces, the situation is completely different. The presence of any sizable separated flow region provides a strong and sufficient energy source for airframe disturbance. The flow field around wings becomes extremely complex in the transonic flight regime, when complicated shock systems interact with the viscous flow field. The influence on separation can be very dominant if the shock strength is sufficiently large to cause a bubble-type separation, which is known as shock-induced separation. Regions of mixed vortex flow with embedded separated areas and unstable shock waves that are present in a 3-dimensional wing flow field at transonic speeds, form the greatest difficulties in describing and defining a precise flow model. Therefore, nearly all investigations involve wind tunnel tests to predict buffet forces.

1.4 Objectives

Because of the complexity of the buffet problem, considerable emphasis is placed on test techniques to obtain various types of wind tunnel data. The target is to provide buffeting boundaries for designers to establish the performance of the aircraft and to produce information about buffeting loads for stressing purposes.

Typical results of buffeting boundaries for a fighter and a transport aircraft are shown in Figure 4. For the fighter, boundaries are defined by buffet onset, which corresponds to the first indication of boundary layer separation. Light buffeting or pilot's onset is defined by the first appearance of a sizable vibration. Moderate buffeting can be said to represent a boundary for a stable weapon platform or a limit for pilot's impairment. Above a boundary, defined by heavy buffeting, the integrity of the aircraft structure is questionable. For a fighter aircraft, the margin to moderate buffeting represents the manoeuvrability in terms of a "n.g" instantaneous pull up or in turn rates (see Figure 1).

With regard to a transport aircraft, a 1.3 g separation from buffet onset to cover light manoeuvres defines the cruise altitude and thus influences the performance of the aircraft considerably. During a normal cruise, the aircraft may encounter a strong gust which carries the aircraft beyond the buffet threshold. Therefore, a 1,6 g separation from maximum penetration, or a definite gust velocity -- for example a normal velocity of 12.5 m/s and a corresponding wave length of 33 m -- must be applied to provide a safety margin for the aircraft structure.

This information can be provided from wind tunnel tests using normal semi-rigid models. The application, however, of the wind tunnel data to establish local buffet loads, vibration levels at any station of the aircraft, predominant frequencies and amplitude ratios for the full scale aircraft, requires some means of accounting for the effects of flight Reynolds number and aircraft structural response, effects which can only be simulated adequately during a wind tunnel test by use of dynamically scaled full aeroelastic models in high density tunnels. In this case, it would be necessary only to record vibration levels via accelerometers at points of interest, and extrapolate the results for the full scale aircraft using similarity rules. Such tests have been performed in the USA by P.W. Hanson (2), Langley Research Center, on a F-111 type model. Although the tests mentioned are done in the USA, one main point is taken from this report, and that is the extrapolation formula, as shown in Figure 5. As mentioned in the report by Hanson (2), parameters k_{n_r}, d_{n_r} and $\left[c_{L,n} (k_n) \right]_r$ should be unity. Small differences in structural or aerodynamic damping can produce differences in the comparison of aircraft to model response. These quantities must be monitored carefully. This statement is one of the central themes in this paper.

It is not clear whether such a model can be designed in Europe in the near future. The problems involved are the design and construction of a model that can withstand large static and dynamic loads at high incidences and high wind tunnel shut down loads. Furthermore, such models are expensive and not readily available.

For these reasons, nearly all European techniques are based on the use of semi-rigid models, and include flight-tunnel correlation factors. Methods covered in this critical review are discussed in subsequent chapters.

2 PREDICTION OF BUFFETING INTENSITY ON THE BASIS OF MEAN AERODYNAMIC LOADS

2.1 Principle

The earliest concepts of deriving buffeting boundaries from normal wind tunnel tests with some reliability were developed by Pearcey and Holder (3, 4). The principles for these methods are derived from the close study of buffeting characteristics of different aircraft in comparison to wind tunnel tests. The conclusion was that the most frequent cause of buffeting is not a localised response to fluctuating pressures, but the result of the direct effects which any kind of separation on a wing exerts on the total loading. The effects on mean loads are, in turn, closely connected with the variation of mean pressure at the trailing-edge through the wing circulation.

The mechanism acting on an airfoil or a wing can be described in brief as follows: if separation on the upper surface of the wing -- due to leading edge, trailing-edge, or shock induced separation, whichever first occurs at relevant Mach number and incidence -- has developed sufficiently to thicken the boundary layer at the trailing-edge position and hence does influence the wake, a rapid fall in pressure on the upper trailing-edge will happen. However, on the lower surface there are no comparable changes in the viscous flow that can give the reduced pressure and that would be necessary on the two sides of the wake, because the wake cannot, in general, support a pressure difference across it. The same pressure as on the upper edge can, in fact, only be achieved by a reduction in circulation. Such a change does provide increased velocities and decreased pressures over the whole lower surface.

Accordingly, the assumption taken by Pearcey and Holder (3, 4) is that the unsteady loads triggered by separation are proportional to the change of the mean aerodynamic loading, i. e., the loss in lift compared to the linear variation with incidence for attached flow as indicated in Figure 6. Locally, the onset of unsteadiness can be derived from the rapid divergence of the trailing-edge pressure compared to the linear variation for attached flow as shown in Figure 6.

The driving buffet force is defined by a lift loss Δc_L or a mean trailing-edge pressure divergence Δc_{PTE}. Structurally, the assumption is made that the aircraft can be treated in a rigid body heaving mode, or that most of the aircraft behave very similar in their elastic response characteristic to a certain degree of excitation, and that the buffeting intensity can be obtained by calibration from flight tests.

2.2 Analysis

2.2.1 Kinkology

Following the hypothesis of Pearcey and Holder (3, 4), outlined above, kinks -- defined by slope changes, rather than by arbitrary irregularities -- in the slope of c_L or c_M versus incidence, are used:

to estimate for

1. Kink = buffet onset
2. Kink = Moderate buffet (2.1)
3. Kink = Heavy buffet

A justification for using the second kink to define moderate buffeting is proven by the fact that the separated flow often rolls up into a vortex. As soon as the vortex influences a sufficient large portion of the wing due to the accompanying lift loss or due to a backward shift of the local c. p. position, either a pitch up or pitch down c_M - kink occurs, which also results in a sudden increase in drag. Thus, the variation in axial force versus α or c_L also can be used as an indication. Figure 7 shows a typical example for those kinks. Although the second kink does not allow the establishment of a quantitative value for buffeting intensities, it gives, in many cases, good correlation to pilot's opinion. It appears that in those cases, the severity of buffeting is not the limiting factor, so that pilot's tend to fly right up to a handling boundary, such as pitch up or wing dropping, which are likely to occur beyond the second kink, as already discussed (see Figure 1).

2.2.2 Simplified Buffet Response Calculation

In Reference (5) C.L. Bore postulates that buffet response is to be measured by peak acceleration (B.g)* suffered by the mass of the aircraft and the fluctuating forces causing buffeting are taken to be proportional to the decrement of lift coefficient as outlined in para 2.1. The expected intensity of buffet response can be estimated from the simple formula

$$B = K \cdot c_B \Big/ \frac{W}{q \cdot S} \qquad (2.2)$$

using the equivalence $\Delta c_L = c_B$, as shown in Figure 8 a where W is the aircraft weight, S is wing area, q is dynamic pressure and K is the constant of proportionality.

The peak acceleration criteria used for various degrees of buffeting are as follows:

$$\begin{array}{lll} \text{Buffet onset} & B \rightarrow 0 & \text{negligible} \\ \text{light} & B = \pm 0.2\ g & \text{peak to peak} \\ \text{moderate} & B = \pm 0.6\ g & \text{" " "} \\ \text{heavy} & B = \pm 1.0\ g & \text{" " "} \end{array} \qquad (2.3)$$

Correlations are presented in Reference (5); an example is shown in Figure 8 b for the Harrier GR1. For this airplane, K = 1 has been found satisfactory. Bore's method does not take into account either the effects of aerodynamic damping or of wing elasticity. The fluctuating force is representing a total aerodynamic force independent of wing motion, and the aircraft response is calculated on the basis of a rigid-body heaving mode.

The analysis presented by Jones (1), which starts from the differential equation for the heaving mode, proves that under certain conditions a heaving response calculation is appropriate. This is possible only when the heaving motion contributes significantly to pilots' impairment, for example, at positions very close to bending nodes at frequencies of 1 - 10 Hz. Then the effect of aerodynamic damping is negligible and vibration intensities satisfy the equation given by Bore (5). Consequently the response is directly proportional to the excitation and likewise to q. Thus at constant true airspeed the response varies linearly with air density ϱ (see Figure 8 b).

2.2.3 Method Based on Trailing-Edge Pressure Divergence

The first suggestion that trailing-edge pressure divergence may be used to predict buffet loads was made by J.C. Winnpenny in the discussion of the paper, Ref. (4). An attempt to predict buffet onset from a divergence of $\Delta c_{p_{TE}}$ = 0,04 - 0,05 at a semispan position of η = 0.85 is certainly too simplified. Husk (6) shows good comparisons, but this is obviously only true for wings that are designed using the same principles. In Figure 9 an example is shown, but the comparison is poor.

A better approach is proposed by Bore (7). The method is based on an analogy of a buffet force coefficient with the normal force coefficient giving:

$$c_N = \frac{N}{q \cdot S} = \frac{1}{0.7 \cdot M_o^2} \quad \frac{n \cdot W}{p_o \cdot S}$$

$$c_B = \frac{B}{q \cdot S} = \frac{1}{0.7 \cdot M_o^2} \quad \frac{b \cdot W}{p_o \cdot S} \qquad (2.4)$$

Where N is the normal force, B is the peak oscillatory normal force; (n.g)*) is normal acceleration and (b.g)*) is the peak oscillatory acceleration. Taking a number of simplifying assumption, Bore used this equation,

$$c_B = \int_{\circ}^{1} \Delta c_{p_{TE}} \cdot \frac{c}{\bar{c}} \cdot d\eta \qquad (2.5)$$

which is a strip-theory analogy to the steady flow relations-ship. The integral can be evalutated graphically for given values of α, and M_o and c_B can be cross-plotted in a c_L against M_o diagramm.

---

* Read: B in fractions of gravitational constant.

*) Read: n or b in fractions of the gravitational constant.

Values for B can then be calculated by the use of equation (2.2). As outlined for equation (2.3) moderate buffeting is then attributed to a value of $B = \pm 0.6$. A schematic example is shown in Figure 10. In applying this method, care must be taken to allow for all the exceptions that can influence the trailing-edge pressure, such as the presence of supersonic flow at the trailing-edge or vortices, which is described in more detail in Ref. (3).

Reliable buffet loads can not be obtained by either of these methods presented in paragraph 2.2.

2.3 Critical Remarks

The methods discussed are a good first approach for defining buffeting boundaries, especially in the lower Mach number area and in cases where no other information is available. Also, in cases where a 2-dimensional type of flow is predominant, the results will be good, because there is almost no margin between buffet onset, moderate buffet and $c_{L_{max}}$. Limitations come in at higher Mach numbers, and in cases where assumptions taken for the dynamic characteristic of the structure are no longer valid.

The following main problems can be defined:

1. The determination of buffet onset on the basis of kinks often leads to too optimistic results. This observation is in accordance with recent experiments of Ray and Taylor (8) on a large number of wings. A possible explanation is that the initial onset of separation that causes a lift loss on one area may be compensated by an increase in lift resulting from a sudden extent of a local supersonic region in an other area of the wing (see Figure 11).

2. If the flow separation starts at the leading edge and extents slowly downstream, then it is obvious that trailing-edge pressure divergence and lift loss due to an overall change in circulation will occur significantly later than buffet onset.

3. Bore's assumption that the aircraft can be treated in its rigid body heaving mode is a limitation which can be adopted only for small fighters with low aspect ratio wings. It must be clearly stated that the elastic behaviour of the structure and the effect of damping can not be neglected in establishing vibration levels. This can be seen from theoretical considerations that in cases where aerodynamic damping is dominant in one mode, then the attained vibration level should be proportional to $\sqrt{\varrho}$ of air density and not directly to ϱ as would result from equation (2.2). But there is a possibility to replace the constant K of equation (2.2.) by a transfer function, which will allow the inclusion of such a dependency on damping.

2.4 Theoretical Methods

Following the principles outlined in paragraph 2.1, Pearcey and Holder (3) proposed a procedure for calculating the buffet onset boundary. The first successful attempt to evaluate transonic buffet limits in a theoretical approach was reported by Thomas (9). Thomas predicted buffet onset assuming that it occurs when shock position and separation - only rear separation can be treated - coincide. According to the availability of theoretical methods, including shocks, Thomas applied only two-dimensional methods. Recently an extension to sheared wing flow was presented by Redeker (10). The application of these methods is limited to wings with a predominant 2-dimensional flow.

A disadvantage in the use of the above methods is that they predict rather large Reynolds number increments in cases where wind tunnel results show little or no influence of Reynolds number. The assumption of Thomas and Redeker (10) that there exists a linear relationship between buffet and the region of separated flow is obviously no longer valid at high Mach numbers and for small thickness ratios.

Since it is, at present, impossible to calculate boundary layer and exciting forces for separated flow, it is impossible to evaluate buffeting intensities.

3. Prediction of Buffeting Intensity on the Basis of the Dynamic Response of Semi-Rigid Models

3.1 Principle

Since buffeting is the dynamic response to an unsteady load, a number of dynamic test techniques and evaluation procedures have been developed during the last few years. Huston (11) suggested a method for predicting the onset of buffeting and flight buffeting loads from measurements of unsteady wing root bending strain performed on semi-rigid wind tunnel models. In order to obtain unsteady wing root bending moments, strain gauges are cemented near the root of the wing on the flexural axis. The method assumes that the reduced frequency of the wing fundamental bending mode is about the same for model and aircraft.

$$f \cdot c_{model} = f \cdot c_{aircraft} \qquad (3.1)$$

Normally on a model, this mode is only slightly damped. Therefore, about 80 % of the total RMS of the wing root bending strain is concentrated near this frequency and can be easily analysed. During a normal test run, the wing root strain signal is recorded and filtered on the basic mode to eliminate influences of the rigging system.*) RMS values can be generated either on line to monitor the test, or after the tests using digital computers, if more and more accurate information is wanted. In Figure 12 a typical plot of the RMS value of the wing root bending strain versus incidence is shown. Up to a certain incidence, $\sqrt{\sigma^2}$ is nearly constant, and from the incidence of buffet onset onward, the signal is rising, comparable to the divergence of trailing-edge pressure.

In this way, buffeting tests can be made simultaneously with conventional force measurements. This method is generally accepted as the most consistent and reliable method of assessing buffet onset from model tests (12, 13, 14). Many flight/tunnel comparisons of buffet onset are available (12, 13, 15). The correlation is in general good to fair, and the method is widely used for comparative tests during the early stages of project studies or for wing design purposes. In order to obtain information about the severity of buffeting, which is closely connected to the post separation onset behaviour of the flow over the wing and the dynamic response of the structure to this excitation, one is left with the problem of scaling the buffeting loads from the model to the aircraft. This problem is difficult to solve because it involves the correct knowledge of the excitation and the transfer function of the elastic system in terms of their quantitative values. In an early stage of a project, this information is not available.

One attempt to overcome those problems is to by-pass the uncertainties and to use the buffeting measurements on semi-rigid models and derive dimensionless buffeting coefficients, and correlate them directly with buffet penetration achieved in flight. Such a method has been developed and presented by Mabey (15), and is in common use in Europe for estimating the buffet penetration capability of aircraft.

3.2 Description of the Mabey Technique

The unsteady RMS value of the wing root strain signal, filtered around the wing fundamental frequency is divided by the dynamic pressure q to give values of

$$c_B\ (\alpha) = \sqrt{\sigma^2}/q \qquad (3.2)$$

which can be plotted against incidence at a given Mach number, (see Figure 12). Mabey assumes that there is a substantial range of incidence at the lower test Mach numbers for which the flow over the wing is attached and for which c_B is constant. This value is denoted c_{Bo}, and can be related to the tunnel flow unsteadiness parameter $\sqrt{n \cdot F(n)}$* at the appropriate Mach number and frequency. The basic hypothesis of Mabey is that $\sqrt{n \cdot F(n)}$ is the exciting force to c_{Bo}, and can be used for calibration; thus it can be written

$$c_{Bo} = K \cdot \sqrt{n \cdot F(n)} \qquad (3.3)$$

A dimensionless coefficient can then be obtained

$$c_B^{\prime}\ (\alpha) = \frac{1}{K} \cdot c_B\ (\alpha) \qquad (3.4)$$

and the relation exists

$$c_{Bo}^{\prime} = c_{Bo/K} = \sqrt{n \cdot F(n)} \qquad (3.5)$$

This evaluation implies that a certain tunnel unsteadiness is necessary, and that the tunnel used must be calibrated with respect to $\sqrt{n \cdot F(n)}$. A typical variation of this quantity with Mach number at constant frequency is plotted in Figure 13. The buffeting coefficient $c_B^{\prime}$ (α) is a direct measure of the generalized force acting in the wing fundamental mode due to any distribution of pressure fluctuations on the wing. The scaling factor K can be regarded as a transfer function representing the dynamic behaviour of the structure in the wing fundamental mode. K is, of course, different for every model and depends on mass, stiffness distribution and total damping of the fundamental wing mode and on details of the instrumentation. Mabey assumes that K is invariant with Mach number. At higher Mach numbers, when even at $\alpha = 0$ some separation on the wing can occur, $c_{Bo}^{\prime}$ will show an increase relative to $\sqrt{n \cdot F(n)}$ (compare Figure 14) but until then, the two curves should be similar, and it is recommended to check the trend with Mach number.

*) for example the sting heaving mode.

$^*\sqrt{n \cdot F(n)} = \frac{\bar{p}}{q} \cdot \sqrt{\epsilon}$ $\qquad \bar{p}$ = unsteadiness in pressure

$\epsilon = \Delta f / f$ analyzer bandwidth

In order to achieve a coefficient $c_B^{\#} = 0$, which corresponds to buffet onset, a reduction to

$$c_B^{\#}\ (\alpha) = \sqrt{c_B^{\prime 2}\ (\alpha) - n \cdot F\ (n)} \qquad (3.6)$$

is proposed by Mabey; however, this is often ill defined, due to a premature creep in the variation of c_B with incidence prior to the rapid build-up of buffet. In order to prove the validity of his method, Mabey has performed a number of tests on a variety of research models at different scale, but always the same planform geometry. The models were built from different material, and had different values for total damping and fundamental frequencies. They were tested at different levels of tunnel unsteadiness but at the same Reynolds number, and he obtained almost the same buffeting coefficients. Mabey then proposed on the basis of flight-tunnel comparisons and based on pilots' opinion, that for any aircraft one can plot c_L against Mach number boundaries defined by:

Mabey criteria

Fighters		Transport aircraft	
$c_B^{\#} = 0$	buffet onset	$c_B^{\#} = 0$	buffet onset
$c_B^{\#} = 0{,}004$	light buffeting	$c_B^{\#} = 0{,}006$	max. penetration
$c_B^{\#} = 0{,}008$	moderate "		
$c_B^{\#} = 0{,}016$	heavy "		

A typical comparison is shown in Figure 15. The poor correlation at M = 0.8 and above can be due to a number of reasons; they are not discussed by Mabey.

The application of the discussed method involves a number of assumptions, and some recommendations are given in Ref. (15), which should be followed to obtain conclusive results. The extrapolation of buffet loads for the full scale aircraft on the basis of buffeting coefficients is explained in Ref. (1), or classical methods (11, 14, 16) can be applied.

A surprising fact in the correlation established by Mabey is that the buffeting boundaries can be obtained in most cases by a dimensionless buffeting coefficient. In those cases it is obviously not necessary to evaluate dimensional local accelerations by use of mode shape factors, nodal line position, generalized masses and damping, although it is doubted that those parameters can be neglegted completely. Some "theories" exist with regard to this phenomenon; The most simple one is that nearly all aircraft behave structurally very similar due to the fact that flutter specialists have carefully designed the structure to the same common principles in order to obtain flutter speeds well outside the flight envelope. The numbers presented in equation (3.7) thus include most of the structural particularities. The difference between maximum penetration of a fighter and of a transport aircraft already accounts for the fact that a pilot on a transport aircraft is more off the nodal line of the fuselage than on a fighter.

Since the dimensionless buffeting coefficient represents a generalized aerodynamic excitation, it is, in any case, possible to produce design charts which show at least trends of the influence on aerodynamic excitation of the main design parameters like section form, sweep back, wing form, wing thickness, and possible improvements by use of manoeuvre slats and/or flaps. Such design charts can well assist the designer in his early project evaluation. A typical example of the influence of sweep on buffeting contours of a swing wing fighter is shown in Figure 16 and of the increments due to well designed manoeuvre slats in Figure 17.

3.3 Critical Remarks

Tunnel results obtained by this method are, in general, good to fair and extremely useful for project studies and comparative tests. The problems associated with the use of the Mabey technique are those which either result from models and the tunnel, or which are by-passed by using statistical correlations and pilots' opinion:

1. Sometimes poor repeatability must be stated. Whether or not this is due to differences in rigging or differences in transition fixing is unclear.

2. Establishing an appropriate K-factor at higher Mach numbers and/or in cases where $c_{B_0}^{\prime}$ and $\sqrt{n \cdot F\ (n)}$ do not show a unique trend, causes considerable difficulties.

3. The imperfections of the model structure can have a negative influence on results. Large changes in mid frequency (see Figure 18) can be reported, which causes problems in establishing proper RMS values. The resulting $c_B^{\#}$ is extremely spiky and shows an irregular variation with incidence. Plateaus, spikes and predivergence creep etc., cause considerable difficulties in the interpretation.

4. On a model, one will find purely structural damping. Imperfections of the model, like a large number of joints, can result in a variation of structural damping with either static or dynamic load (see Figure 18). Since the variation of structural damping on those models which form the basis of Mabeys tunnel-flight correlation is not known, it is unclear whether results obtained with varying damping must be corrected or not.

5. In flight, most of the buffeting at the pilot's station, (see Ref. 2), is in second and third structural modes, because the total damping in those modes is smaller than for the first wing bending mode. This fact casts some doubt on the assumption of Mabey that there exists a linear correlation of intensities between pilot's station and the wing root fundamental bending strain. In cases where unstable shocks at frequencies outside natural ones produce large amounts of energy, a forced mode can be established. This effect can even be found on semi-rigid models, as is shown in Figure 19. This forced mode is however not taken into account by the Mabey technique due to the application of a filter around the fundamental mode.

4. Methods Using Fluctuating Pressure Measurements

4.1 Principle

Methods discussed so far give relatively good results about exciting forces, but the structural problems are either oversimplified or by-passed by using statistical correlations. Thus the extrapolation to the full scale aircraft is in many cases questionable. There are two fundamentally different methods of predicting the buffeting intensity composed from the main modes starting from wind tunnel measurements on models. The first one uses dynamically scaled aeroelastic models. This has been discussed already in paragraph 1.4. The second one starts from measurements of the pressure fluctuations on a semi-rigid model and then calculates the dynamic response, when these pressures act on the flexible structure. A survey of the problems involved in this second possibility of an approach is given by Moss (17). The first attempt to perform such calculations was done by Mitchell (18) on a Concorde type of wing. No flight to calculation comparison has been published by Mitchell.

A detailed analysis of the different possible concepts for this approach is given by Jones (1). According to the principles outlined by Jones, the difficulty that arises is encountered in the difference in dynamics of the structure of a quasi-rigid wing (model), having small amplitudes only and in the full scale aircraft having rather large amplitudes at buffeting conditions. Two main cases can be distinguished:

1. Forced vibration model

   This consists of random pressure fluctuations, which are independent of wing motion. The motion in turn produces an additional pressure field (oscillating pressures), which provides the aerodynamic damping. The appropriate model is "nonautonomous" and a linear analytical formulation is adequate.

2. Non-linear flutter model

   Here the driving forces depend in a deterministic way on the motion of the wing. The appropriate model is "autonomous" and a nonlinear analytical formulation is essential.

The main problem that arises for the theoretical approach is the fact that the transition from the first case to the second is fluent, and the amplitude of the wing motion is a relevant parameter.

4.2 Theoretical Model and Assumptions

A software package for the application of PSD concepts for buffeting analysis is presently under development in Germany, and is monitored by the author (19). Details of the recording system and the equations used can be taken from Ref. (19). A brief verbal description is presented here only, due to the rather complicated equations; on the other hand there is nothing new about the application of statistical concepts, like correlation functions, power spectral density (PSD) and RMS values in aerodynamics.

A linear theory, the so-called "forced vibration model", (see Figure 20) has been adopted to be applied in the area up to moderate buffeting only, assuming that on the aircraft up to this limit the amplitude of the wing motion is small (see above). The calculation is starting from the differential equation of motion

$$M \cdot \ddot{x} + D \cdot \dot{x} + C \cdot x = P_{\ddot{x}} + P_{\dot{x}} + P_x + P_{Buffet}, \qquad (4.1.)$$

where the left hand side represents the structure and the right one the aerodynamic quantities. M is the equivalent mass, D a viscous damping, C the stiffness, x the amplitude and the dotes the derivatives with time. P with index is the appropriate aerodynamic force and P_{Buffet} represents the exciting force due to buffet. The structural model is equivalent to those used for gust response calculations. The

solution of equa. (4.1.) is, therefore, well known and typically reported in (19, 24).

For a semi-rigid model, the assumption can be made that the amplitudes are negligibly small, so that buffet forces are acting on the surface only, which can be recorded via dynamic pressure pick-ups. For the investigation, fluctuating pressures have been recorded using a 5th scale half model, as shown in Figure 21. A half model was selected to provide sufficient thickness for installing the total equipment, as there was: 44 static pressure tappings, 19 unsteady pressure pick-ups, 6 accelerometers and a wing root strain gauge. The following pictures will show some typical results. In general, it can be stated that the power spectral density is flat, dropping at a distinct frequency (see Figure 22). In cases where unstable shocks appear, the spectrum is showing a local maximum, and the accelerometers indicate a forced mode at this frequency, often near the natural torsion mode (see Figure 23 and 19).

Using pre-established mode shapes for a number of natural frequencies, generalised forces can be generated using such records. The next step is to calculate autocorrelation and cross-correlationfunctions for use with the structural model. As a final result, power spectral densities of local accelerations in fractions of the gravitational constant can be obtained at any station of the aircraft. From the response calculation at the station of the pilot, an assessment of the pilot's impairment can be achieved using the ISO-Standard method (20). Another approach to assess the pilot's limitations is to accummulate signals of the different frequencies using weight factors for different frequencies according to Ref. (20) and calculate a total RMS buffeting acceleration. This value can be transformed to a peak-to-peak normal buffeting acceleration, using a criterium according to equation (2.3), buffeting boundaries can be established. Three typical results of local PSD plots -- at wing tip, strain gauge position and pilots seat -- are to be seen in Figures 24, 25, 26.

Up to now, the calculations are simplified insofar as a wing-body combination can be treated only.

The brief description given above does already indicate that an extensive computation effort is needed. Hence, a limited number of measurements and calculations are available only.

4.3 Damping

For the final calculation, oscillating pressures due to the motion of the wing and denoted in equa. (4.1) $P_{\ddot{x}}$, $P_{\dot{x}}$, P_x, must be introduced, and a number for the structural damping of each mode must be adopted. For the investigations mentioned above, the structural damping is varied between 3 % and 5 %, and can be finally assessed from ground vibration tests of the aircraft. Oscillating pressures are calculated according to a method described by Laschka (21), assuming attached flow. The aerodynamic damping, as obtained by theory for attached flow, is considered to be linear; that means the coefficient of damping is a constant for all amplitudes of oscillation.

Flight test results performed recently by Jones (22) on a fighter aircraft indicate, as can be seen from Figure 27, a large variation of "apparent" damping in the wing fundamental mode with incidence. Test results reported by Rainey (23) on harmonically excited models also show a variation with incidence, although not to the same extent as given in Figure 27. When it is recalled that the increase occurs beyond buffet onset where steady force coefficients are also nonlinear, it is unlikely that the assumption of linear characteristics during buffeting will be valid. Thus, the calculation will be pessimistic with regard to the fundamental wing mode.

4.4 Remarks

Up to now, only theoretical approaches and discussions are published. Mitchell (18) has never circulated results of Concorde flight tests. The flight tests for the evaluation of John (19) have not yet been started. The lack of correlation information with which one could obtain the accuracy of the method is certainly a disadvantage. On the other hand, it is obvious that measured pressure fluctuations on a structurally responding wing - as on a flying aircraft - are difficult to interpret on a quantitative basis, owing to mutual cancellation of aerodynamic excitation and aerodynamic forces at the natural frequency of wing motion. Thus, vibration levels and buffeting design loads can be correlated only.

Due to a number of uncertainties and simplifications, some short comings must be expected. Nevertheless one can perform a number of comparative studies in a parametric way and gain in experience about the behaviour of an aircraft beyond the buffet boundary, and more basic research is wanted in this area.

5. Conclusions and Objectives for Future Research Work

Several methods -- for some various techniques of analysis -- are thus available to the specialist interested in buffeting information. Particular considerations in each case will guide the individual choice: availability of models or appropriate tunnels and means of analysis.

The most favourable, but most expensive test technique implies obviously the use of dynamically scaled flexible models. The required information, however, will

come relatively late in a project stage and will not influence the configuration directly. For early design phases and comparative tests on alternative wing designs, the application of the Mabey technique is recommended. The extensive computing facilities that are needed to obtain buffeting levels and loads using the PSD-concept will limit this method to an application for check out in critical areas or for specific design problems only. The relation between buffeting intensities and mean loads is restricted to relatively rigid aircraft. An extension to include dynamic response characteristics of the structure is wanted.

Of major importance for all methods discussed is the influence of damping on the attained vibration level. It is recommended, therefore, to monitor the possible variation of damping with incidence on models and on aircraft to provide detailed information and means of correlation. More research work is wanted in this area to eliminate contradictory conclusions.

For many years it is known that separation has a derogatory effect on aircraft performance. Therefore, much effort has been concentrated on improving theoretical methods of wing design to avoid early separation. Possibilities to control the growth of separation beyond buffet onset and to obtain by such means a more gradual development of buffet forces with incidence, are not studied in sufficient depth. Most of our knowledge about fences, notches, vortex generators etc., has been obtained through trial and error and has proven to be successful. As there is an increased trend toward the use of fluctuating pressure measurements for the study of buffeting, a research program should be initiated to investigate means of controlling the growth of separation. This would help to put our understanding of the phenomenon on a firmer footing.

Furthermore, high Reynolds number test facilities are needed to eliminate the uncertainties which arise in the extrapolation to the full scale flow conditions.

Finally it must be stated here that a method to predict tail buffeting loads in turbulent wake flow is practically nonexistent.

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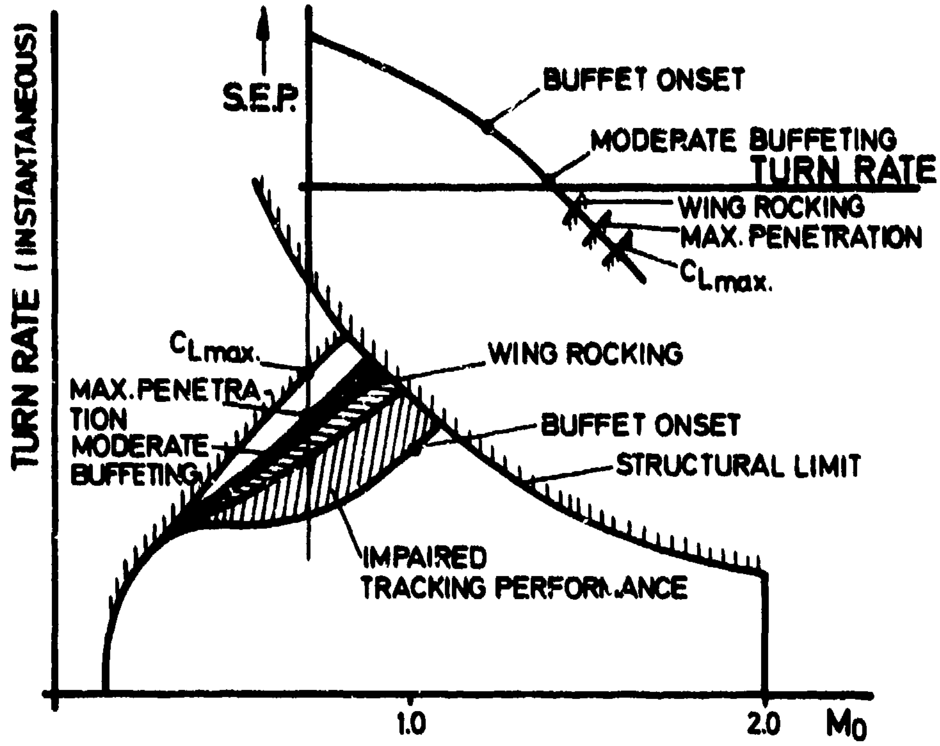


Fig. 1: Principle of Manoeuvre Boundaries for a Fighter Aircraft

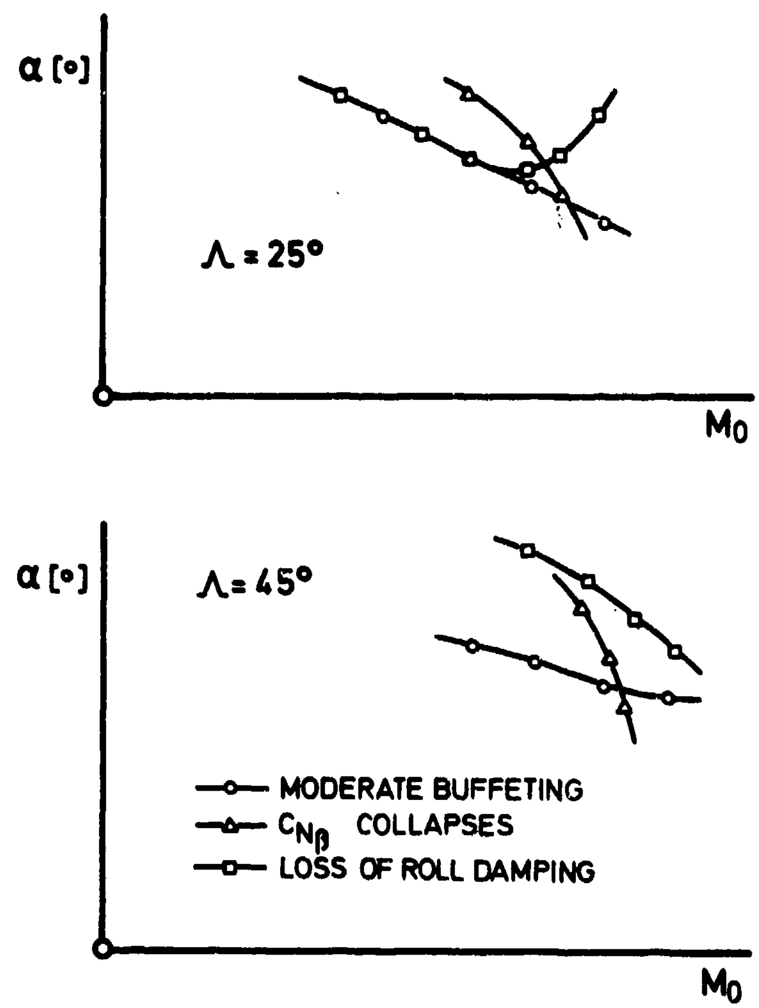


Fig. 2: Summary of Manoeuvre Limiting Phenomena

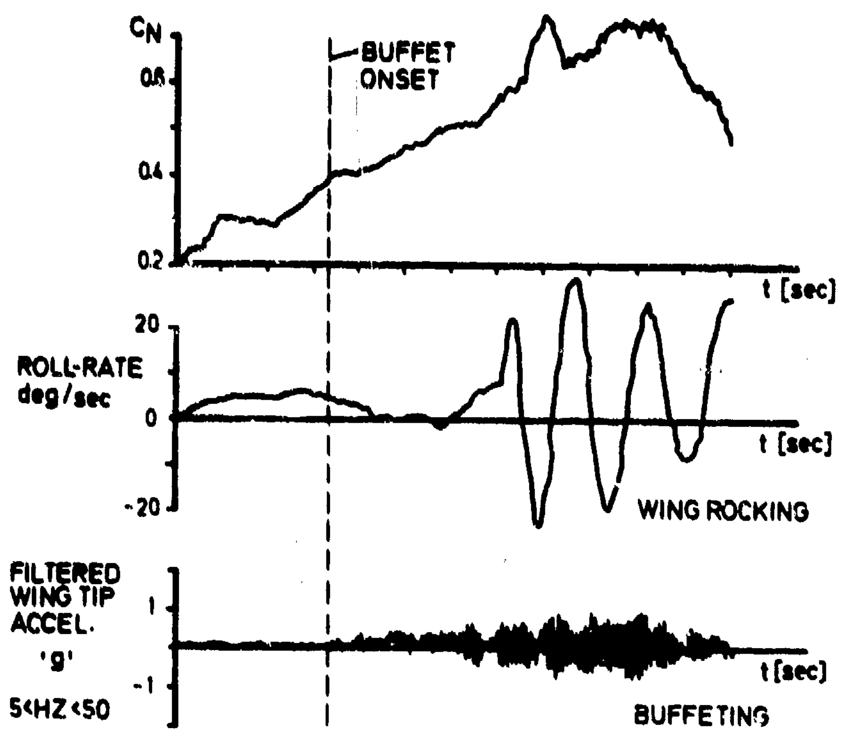


Fig. 3: Typical Penentration to High c_N of Fighter Type Aircraft

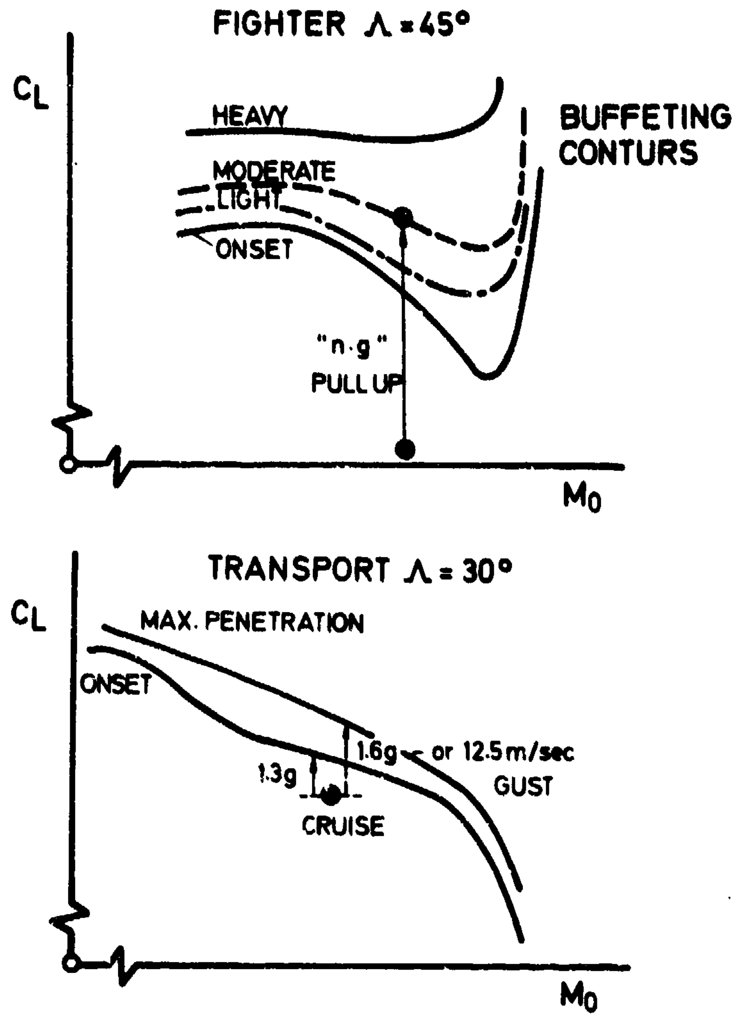


Fig. 4: Buffeting Criteria

$$a^2(\eta_0)_{T,A} = b_r^4\, q_r^2 \sum_{n=1}^{\infty} K_{n,r}\, \frac{1}{m_r^2}\cdot\frac{d_{n,M}}{d_{n,A}}\cdot\left[\hat{C}_{L,n}(K_n)\right]_r\, a^2(\eta_0)_{n,M}$$

NOTATION :

$a(\eta_0)_{T,A}$	AIRPLANE TOTAL ROOT-MEAN-SQUARE BUFFET ACCELERATION AT PARTICULAR LOCATION.
b_r	SCALE FACTOR .
q_r	AIRPLANE TO MODEL DYNAMIC PRESSURE RATIO
$K_{n,r} = \frac{b_r \cdot \omega_{n,r}}{V_r}$	REDUCED FREQUENCY A/M-RATIO FOR nth NATURAL VIBRATION MODE.
$\left[C_{L,n}(K_n)\right]_r$	A/M-RATIO OF POWER SPECTRUM OF EFFECTIVE RANDOM AERODYNAMIC LIFT COEFFICIENT.
$d_n = \left[\left(\frac{C_a}{C_{cr}}\right)_n + \left(\frac{C_s}{C_{cr}}\right)_n\right]$	SUM OF AERODYNAMIC AND STRUCTURAL DAMPING IN nth VIBRATION MODE
$a(\eta_0)_{n,M}$	MODEL RMS BUFFET ACCELERATION IN nth VIBRATION MODE AT PARTICULAR LOCATION.

Fig. 5: Extrapolation Formula for Buffet Loads

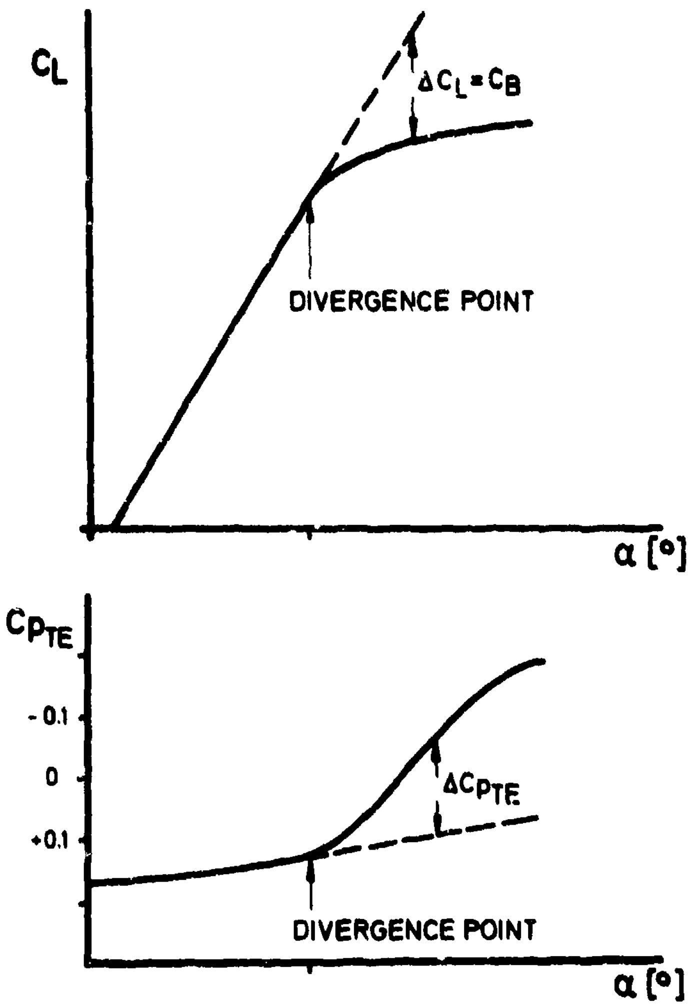


Fig. 6: Correlation between Divergence in Trailing-Edge Pressure and Lift Coefficient Variation.

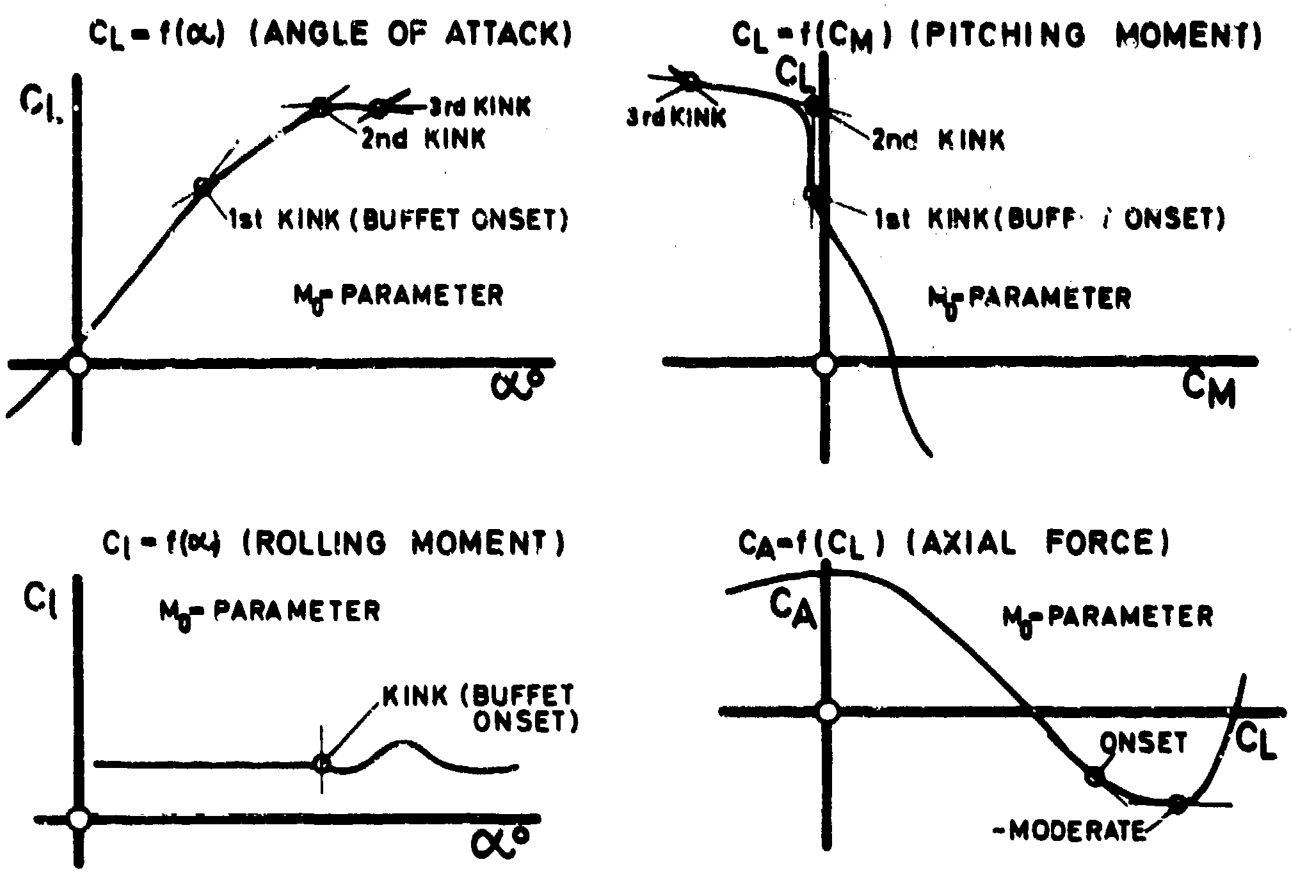
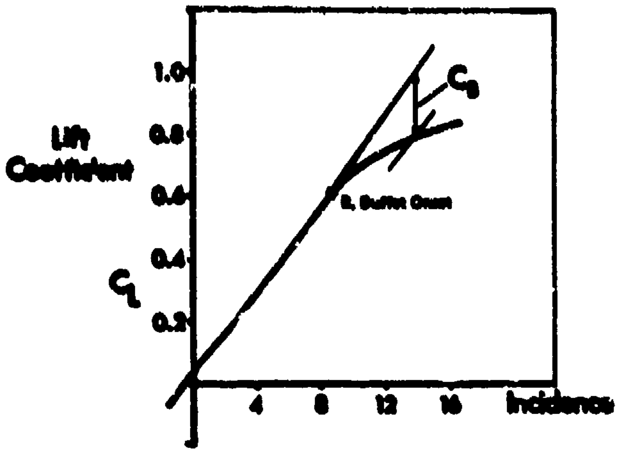


Fig. 7: Definition of Kinks



$$B = K{\cdot}C_B \,/\, \left(\frac{W}{q \cdot S}\right)$$

MODERATE BUFFETING $B = \pm 0.6\,g$

WHERE W IS THE AIRCRAFT WEIGHT, S IS WING AREA, q IS DYNAMIC PRESSURE AND K = 1 HAS BEEN FOUND SATISFACTORY FOR THE CONSTANT OF PROPORTIONALITY

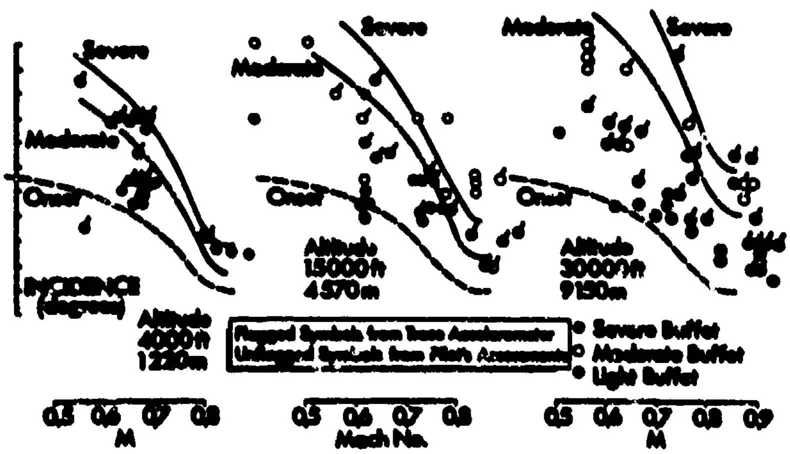


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Fig. 8: Simplified Buffet Response Calculation

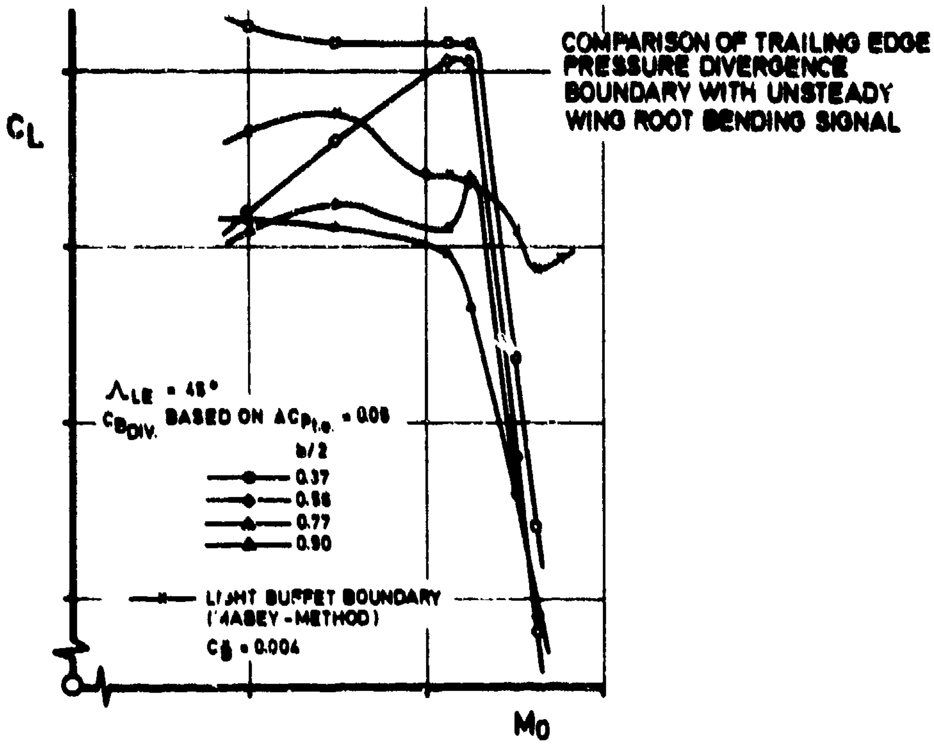

Fig. 9: Definition of Buffet Onset

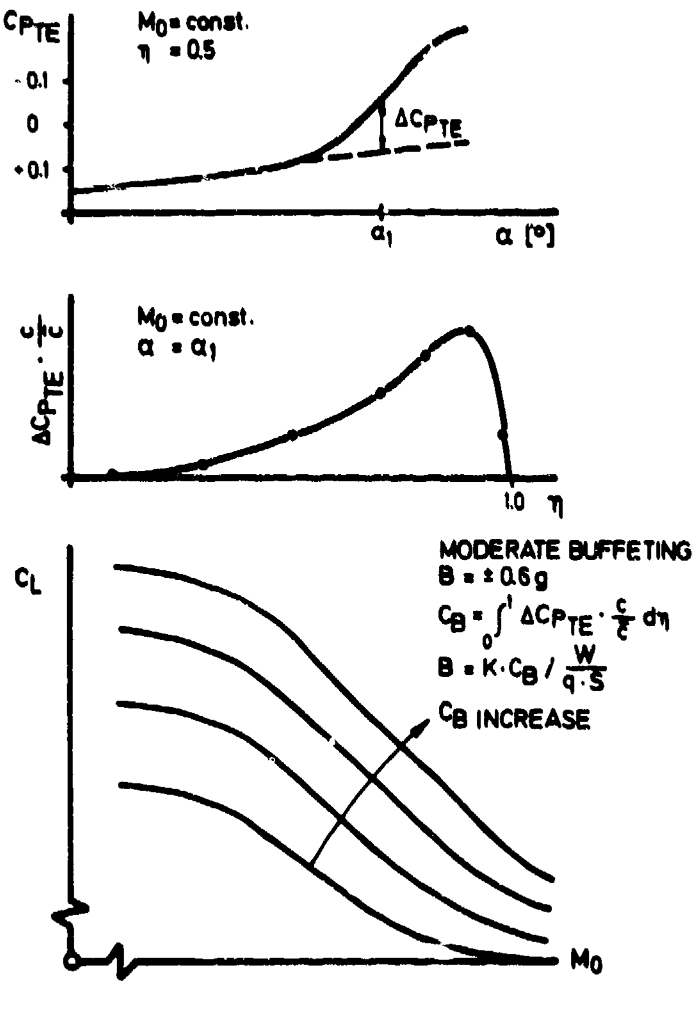

Fig. 10: Buffet Response Calculation by Use of Trailing-Edge Pressure

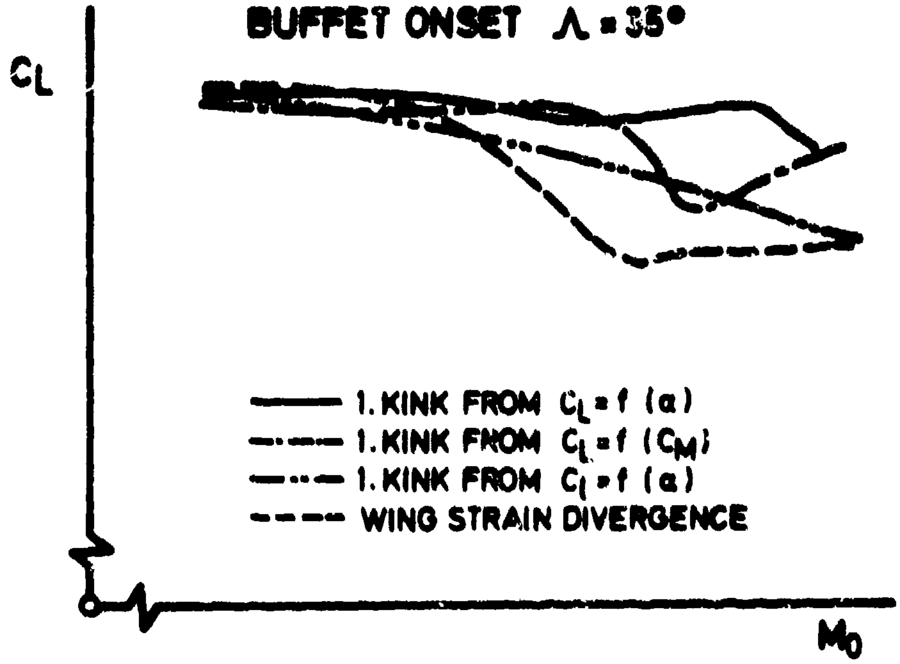

Fig.11: Comparison of Different Buffet Onset Criteria

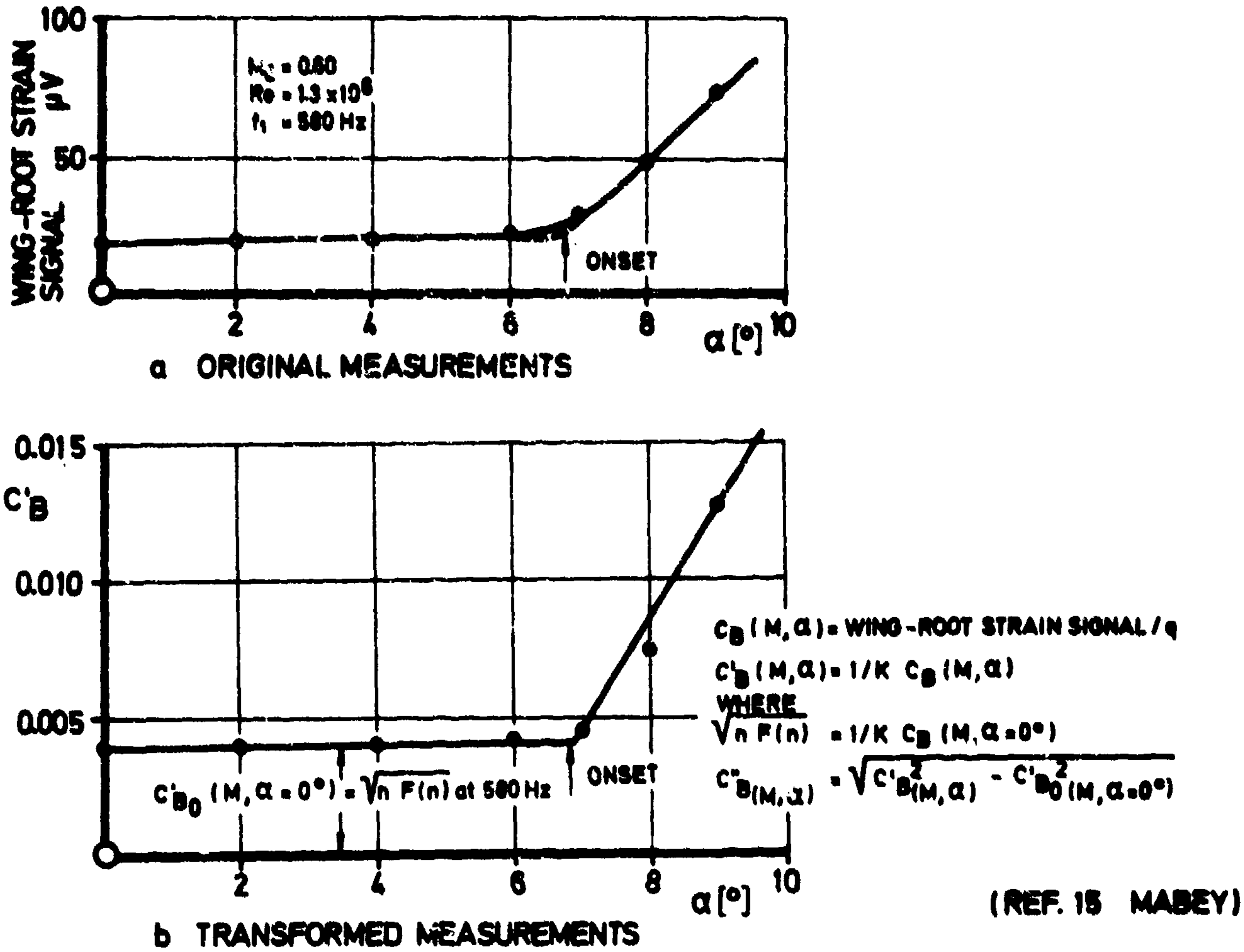

Fig. 12: Definition of Buffeting Coefficients

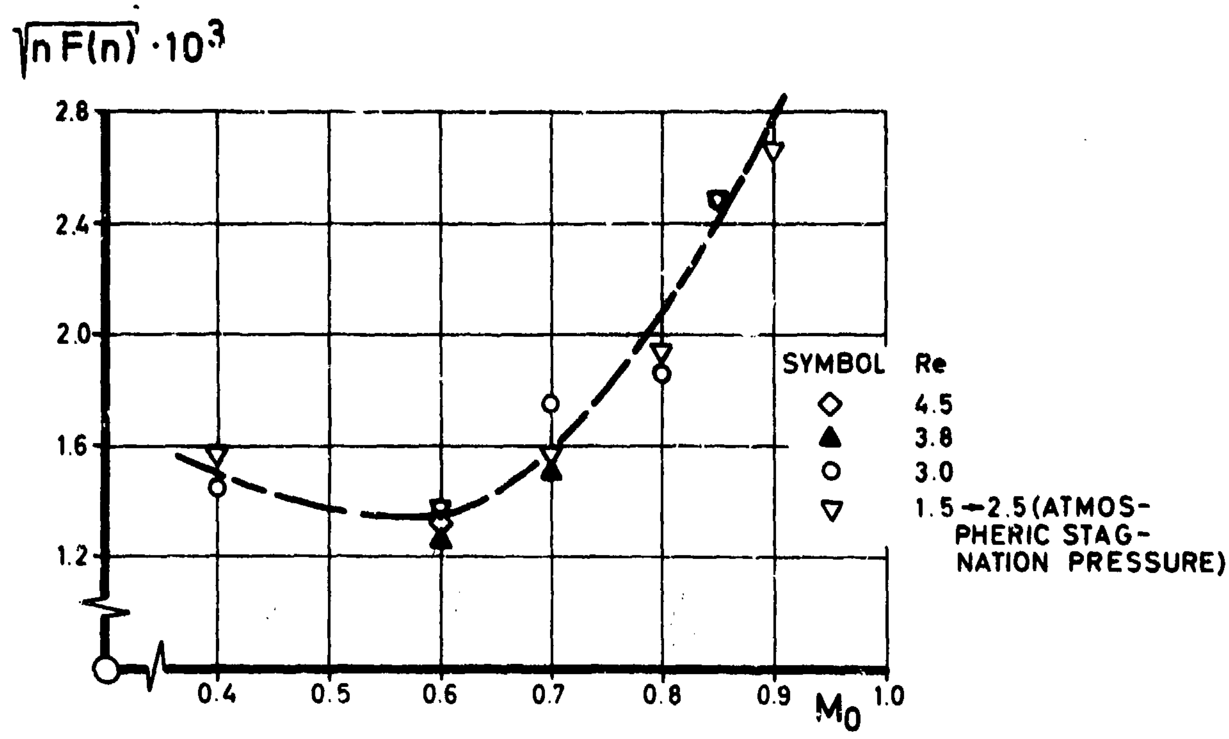

Fig.13: Typical Variation of Tunnel Unsteadiness with Mach-Number and Tunnel Stagnation Pressure

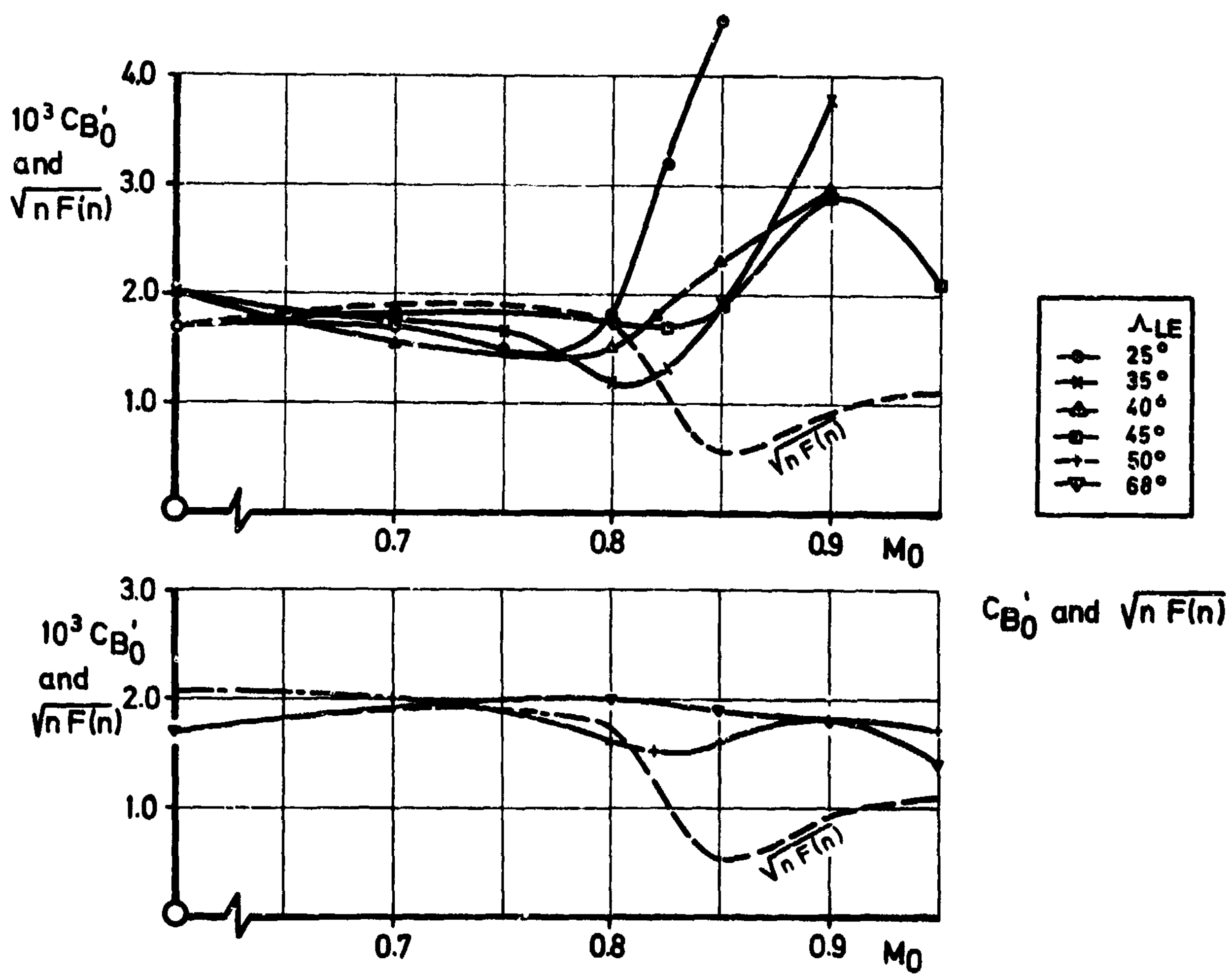

Fig.14: Low Level Buffet and Tunnel Noise

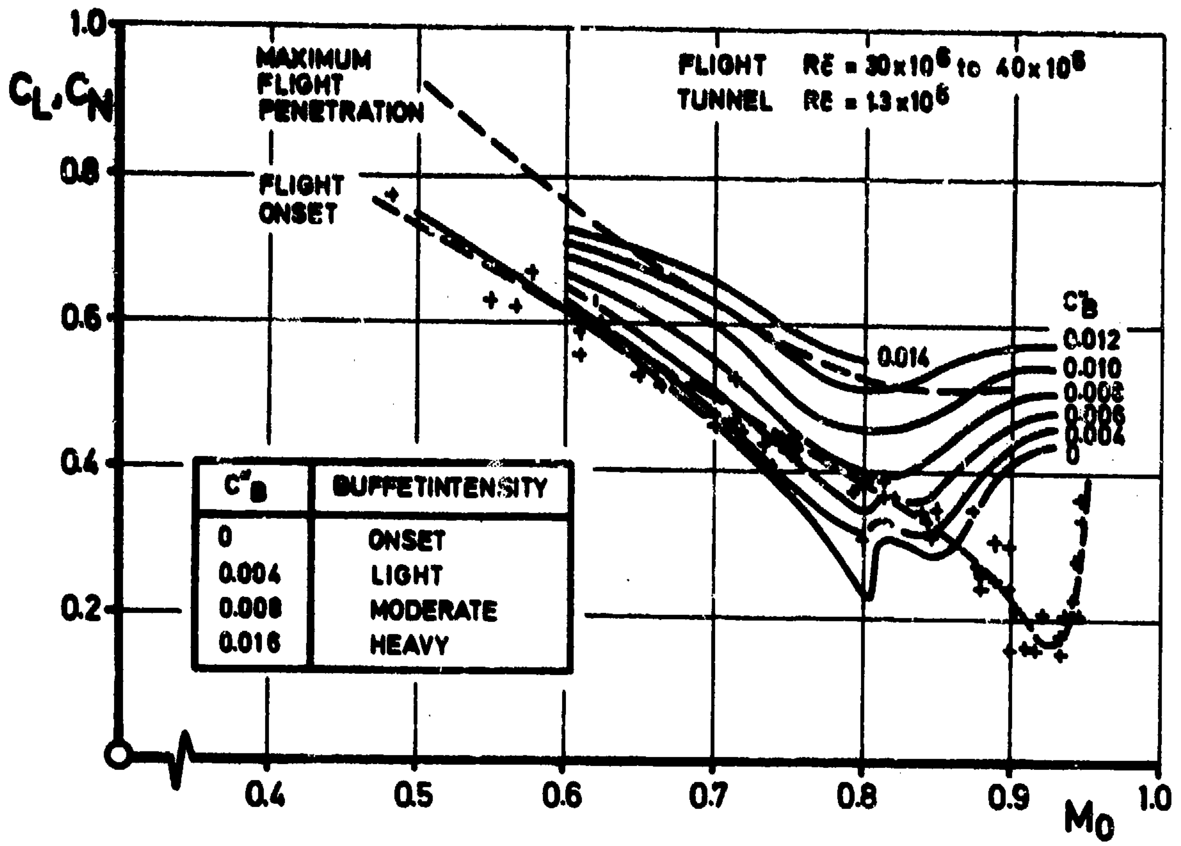

Fig.15: Correlation of Model Buffeting Coefficient with Flight Data

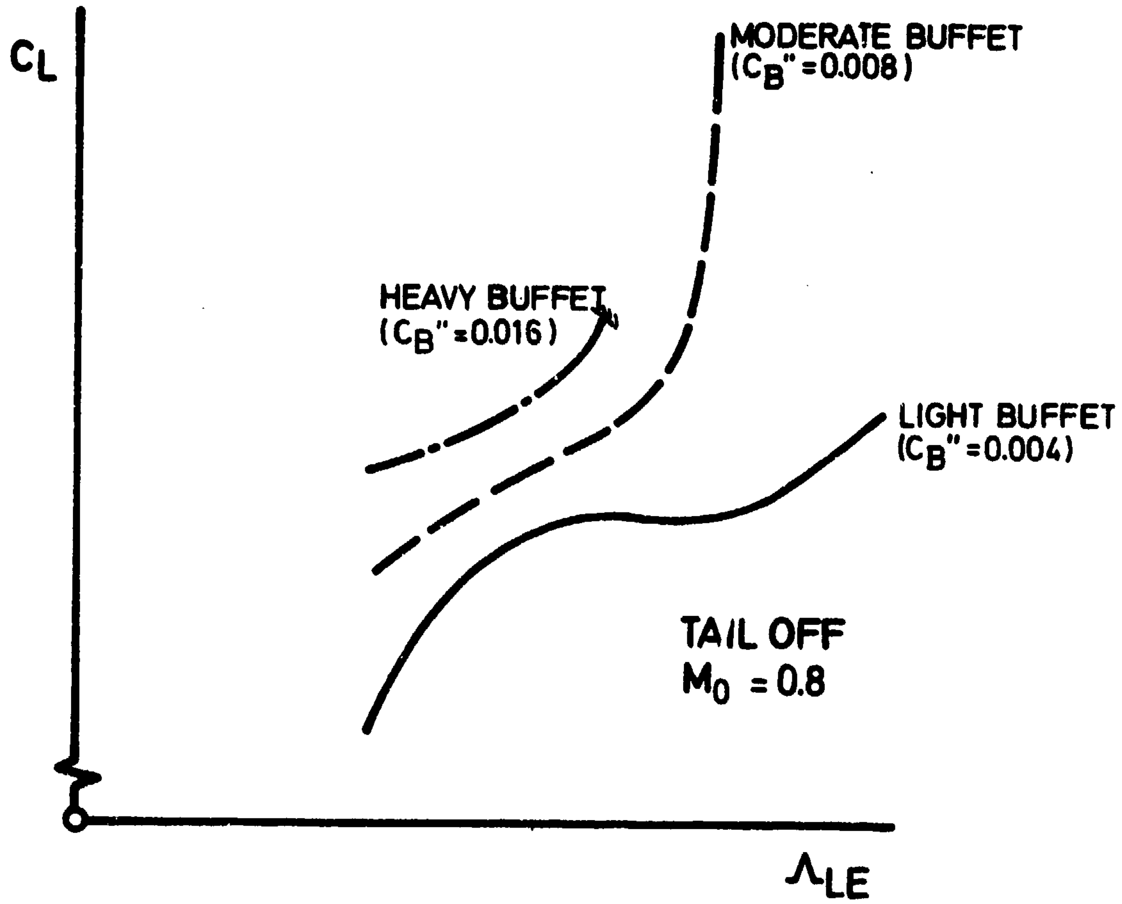

Fig.16: Effect of Wing Sweep on Buffeting Penetration

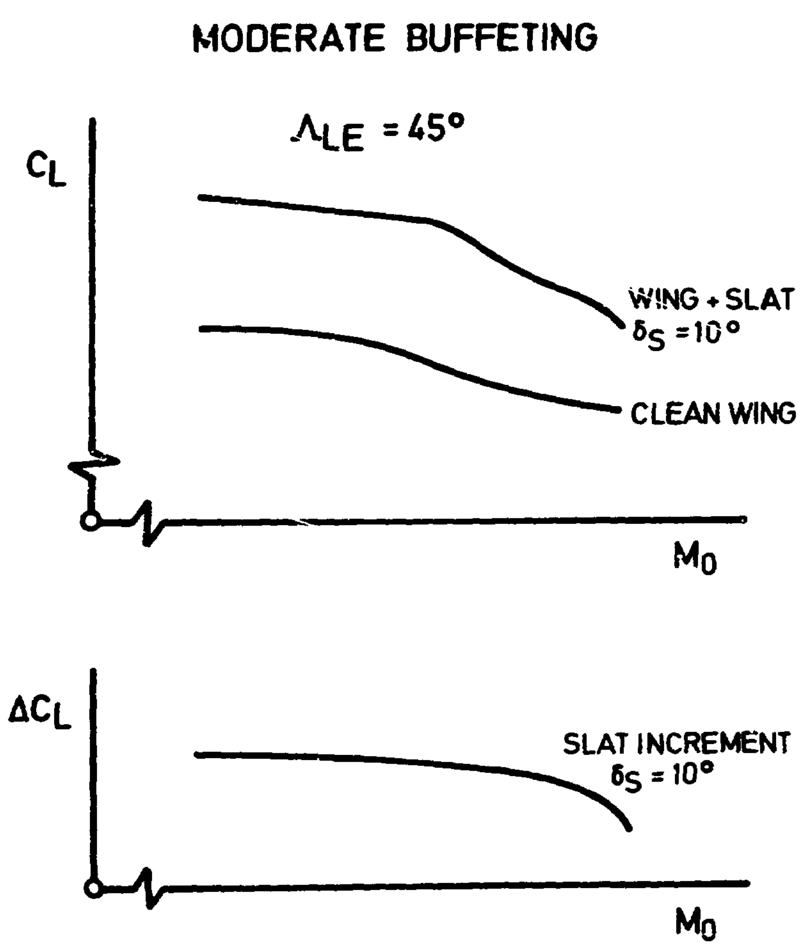

Fig.17: Effect of Manoeuvre Slat

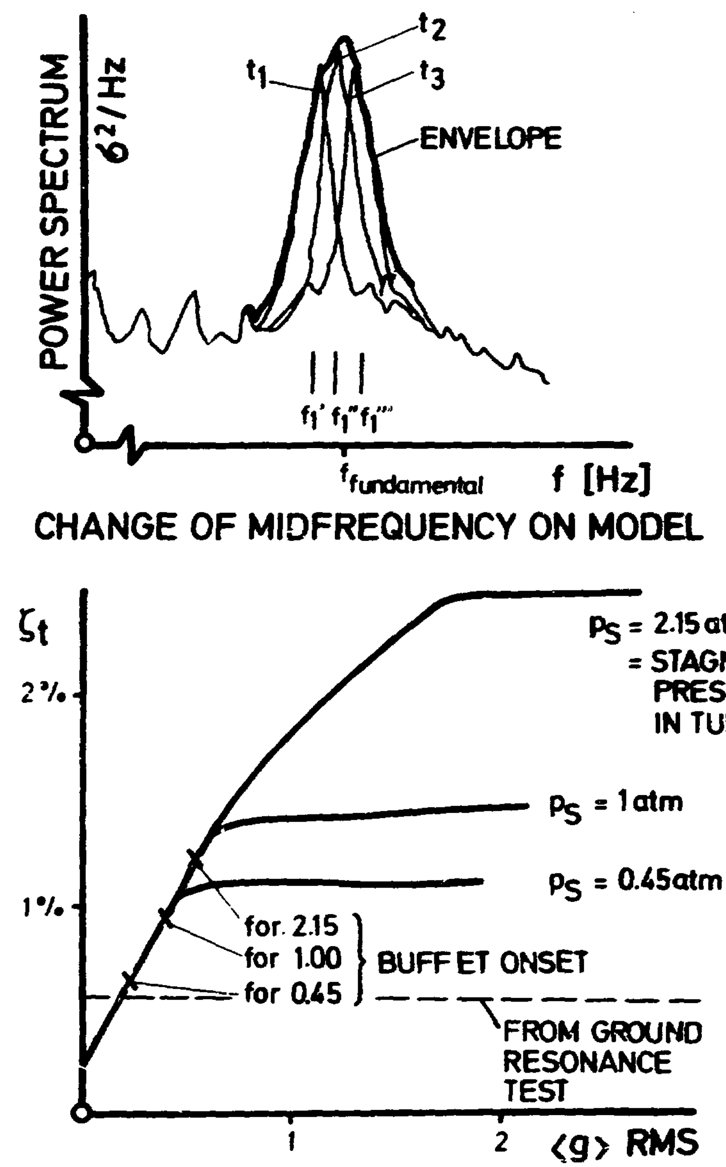

Fig.18: Total Damping versus Acceleration Level on Model

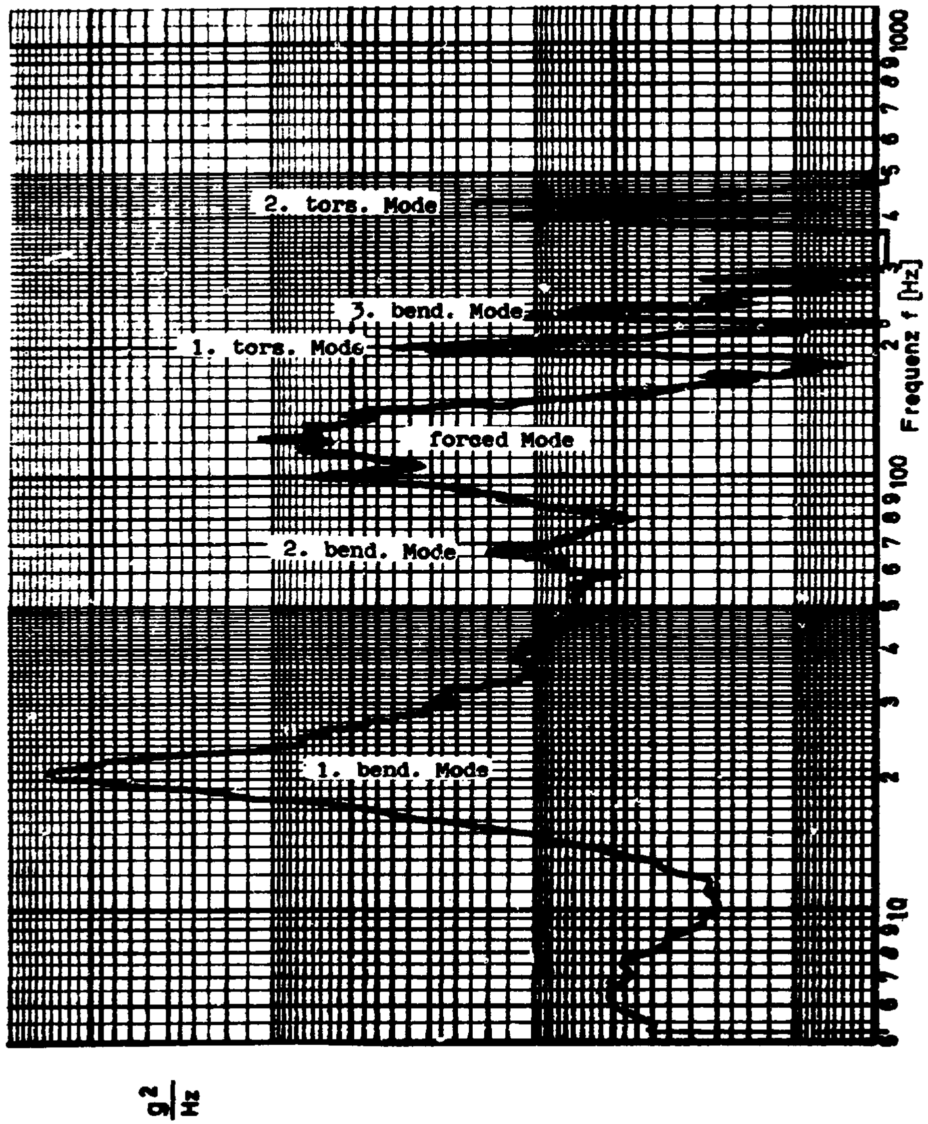

Fig.19: Power Spectrum of Accelerometer on Model

$$M \,.\, \ddot{x} + D \,.\, \dot{x} + C \,.\, x \;=\; P_{\ddot{x}} + P_{\dot{x}} + P_x + P_{Buffet} \qquad (4.1)$$

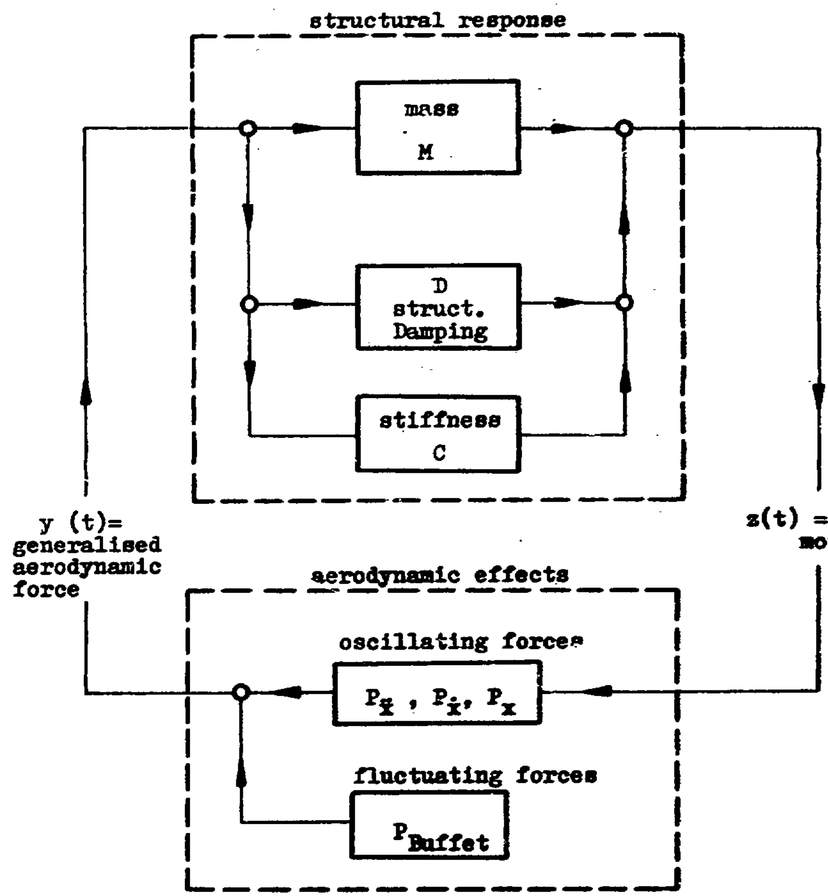

Fig.20: Block Diagram for Structural Buffeting, Representing Response in Flexible Mode.

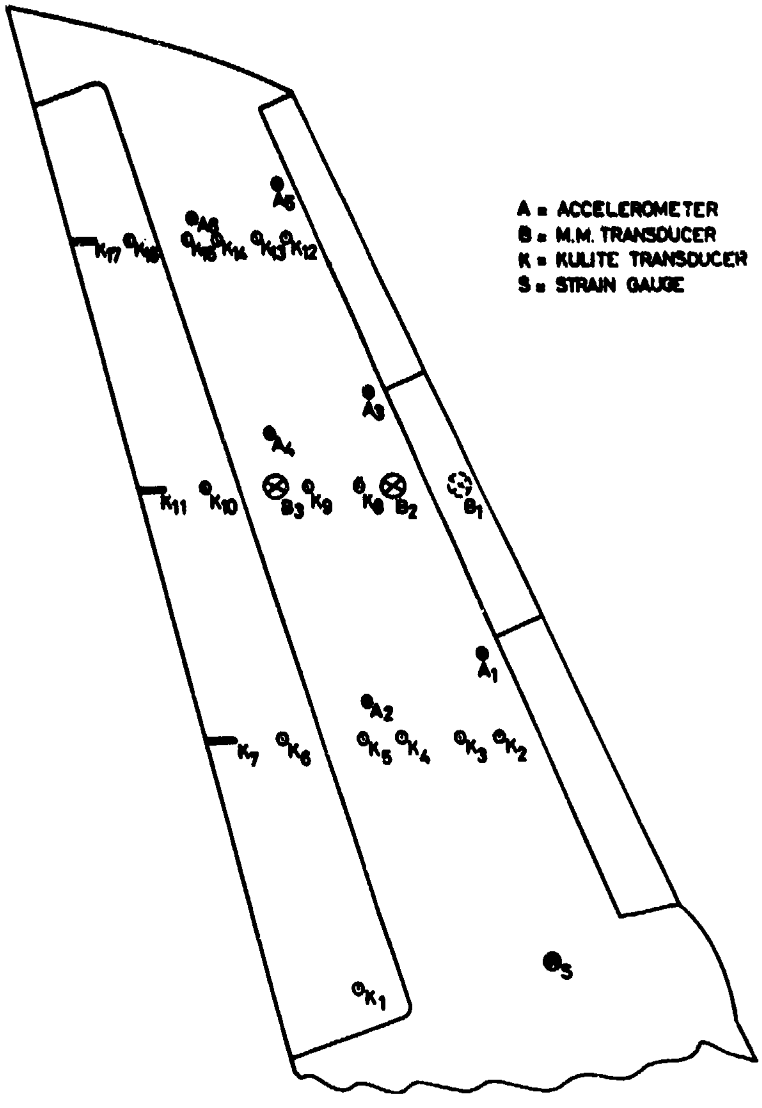

Fig.21: Clean wing Upper Surface with Transducer Positions.

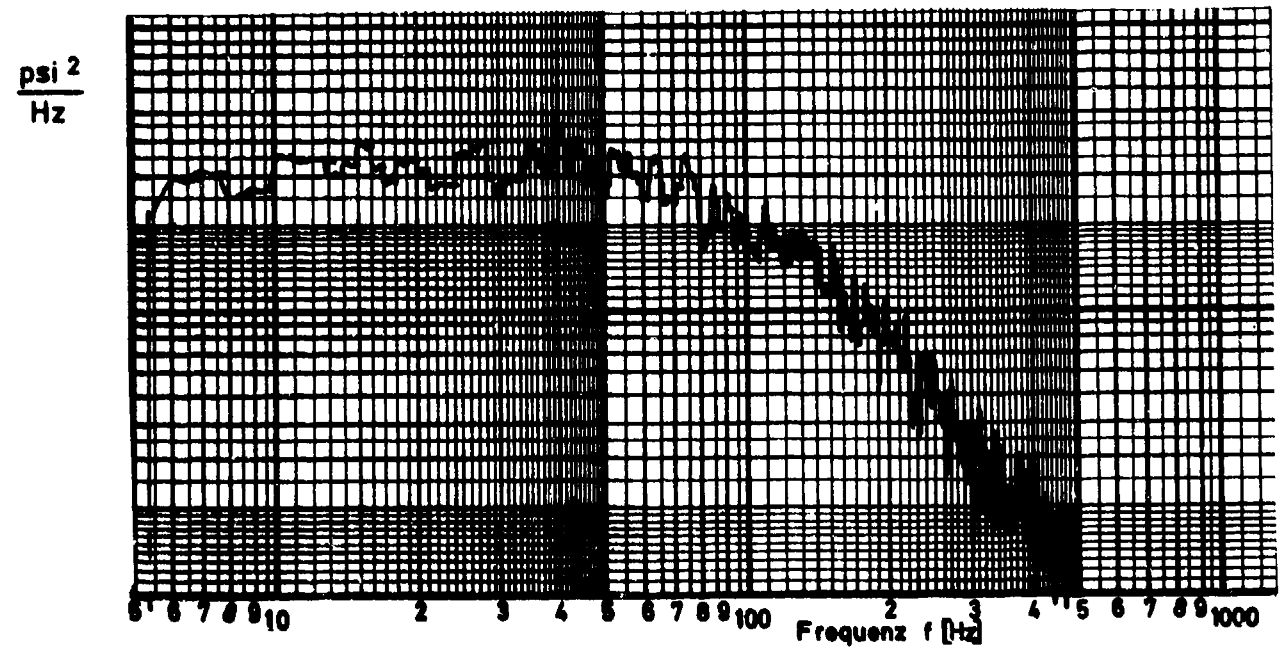

Fig.22: Power Spectrum of Pressure Fluctuation on Model at Midspan.

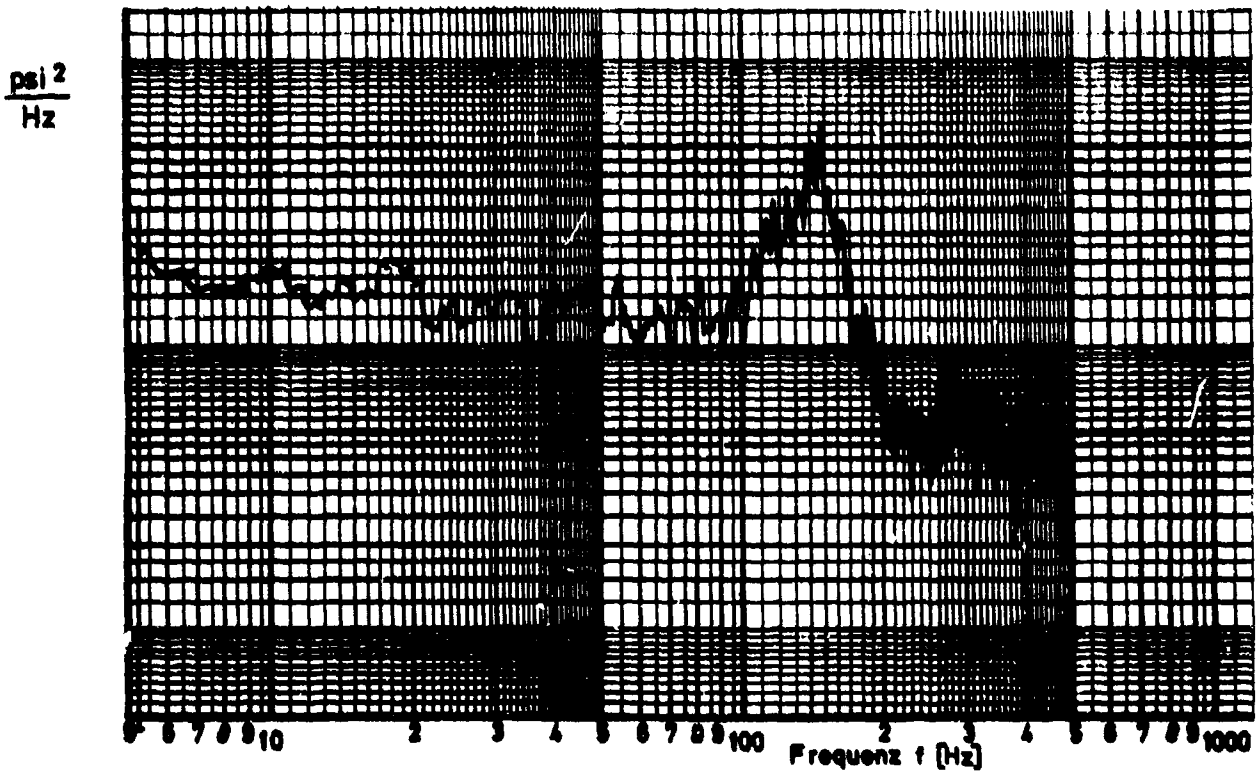

Fig.23: Power Spectrum of Pressure Fluctuation on Model near Tip.

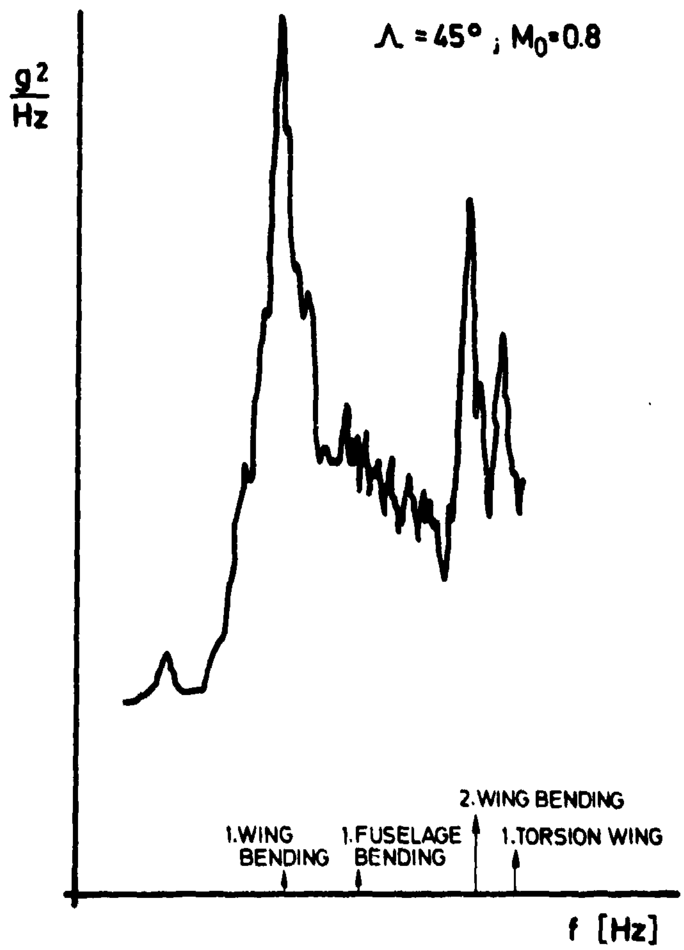

Fig.24: Buffeting Response Calculation.
Power Spectrum at Wing Tip.

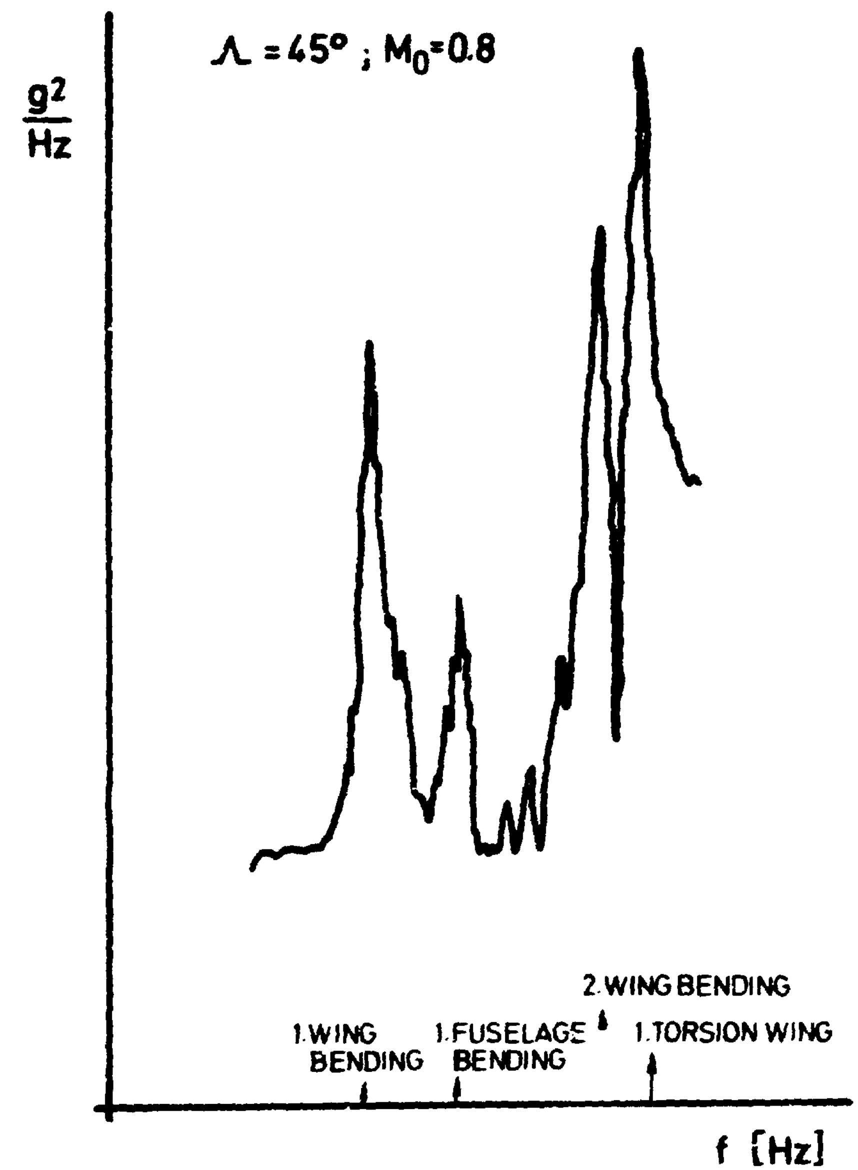

Fig.25: Buffeting Response Calculation. Power Spectrum at Wing Root.

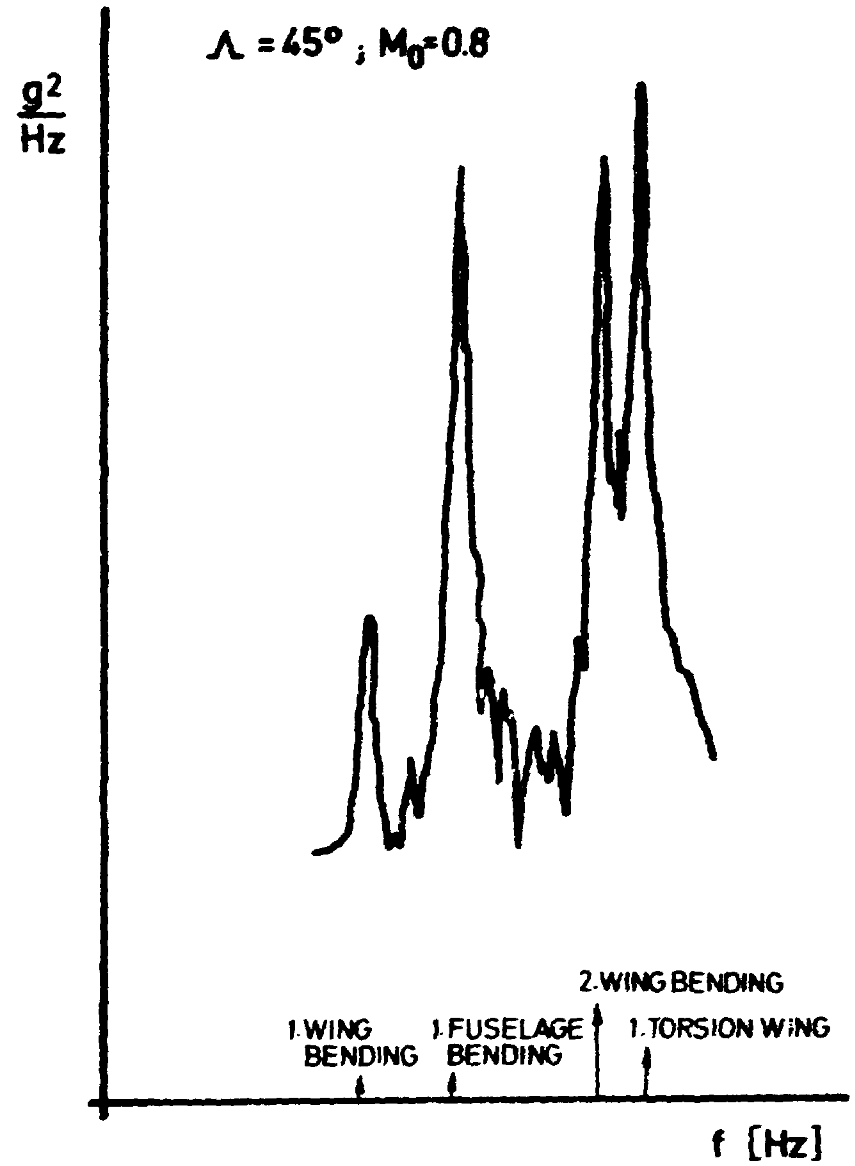

Fig.26: Buffeting Response Calculation Power Spectrum at Pilot Station.

RAE FLIGHT TESTS

from Ref. [22]

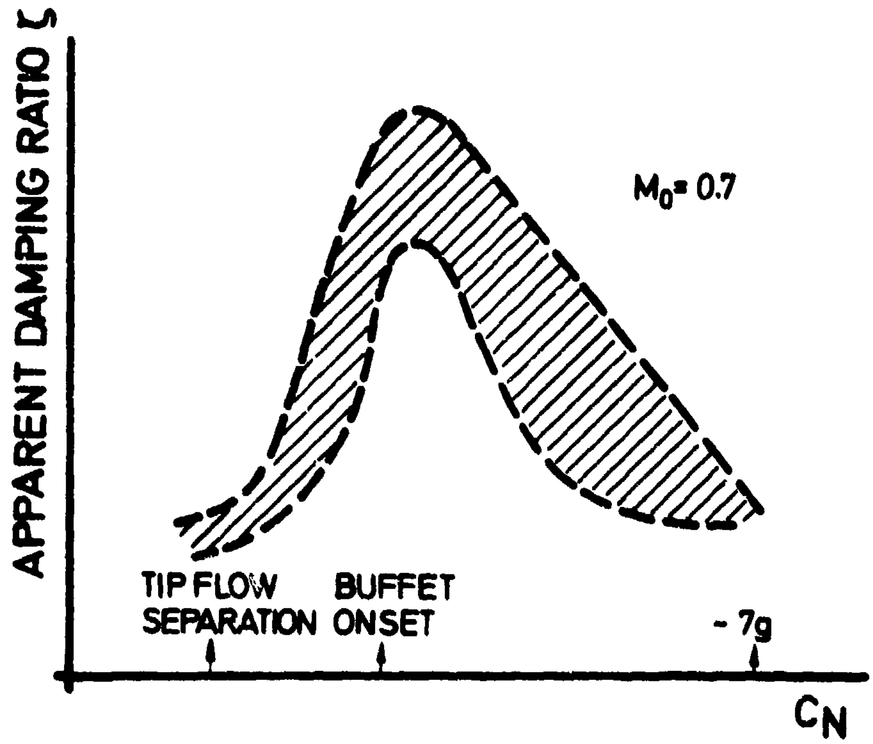

Fig.27: Damping in Wing Fundamental Mode during Buffet Penetration.